Advanced Modeling & Simulation (AMS) seminar series, NASA Ames. R. C. March 7 2018

Large-scale LES Analysis in Real Industrial Applications

- From the historical perspective of CFD -

Kozo Fujii

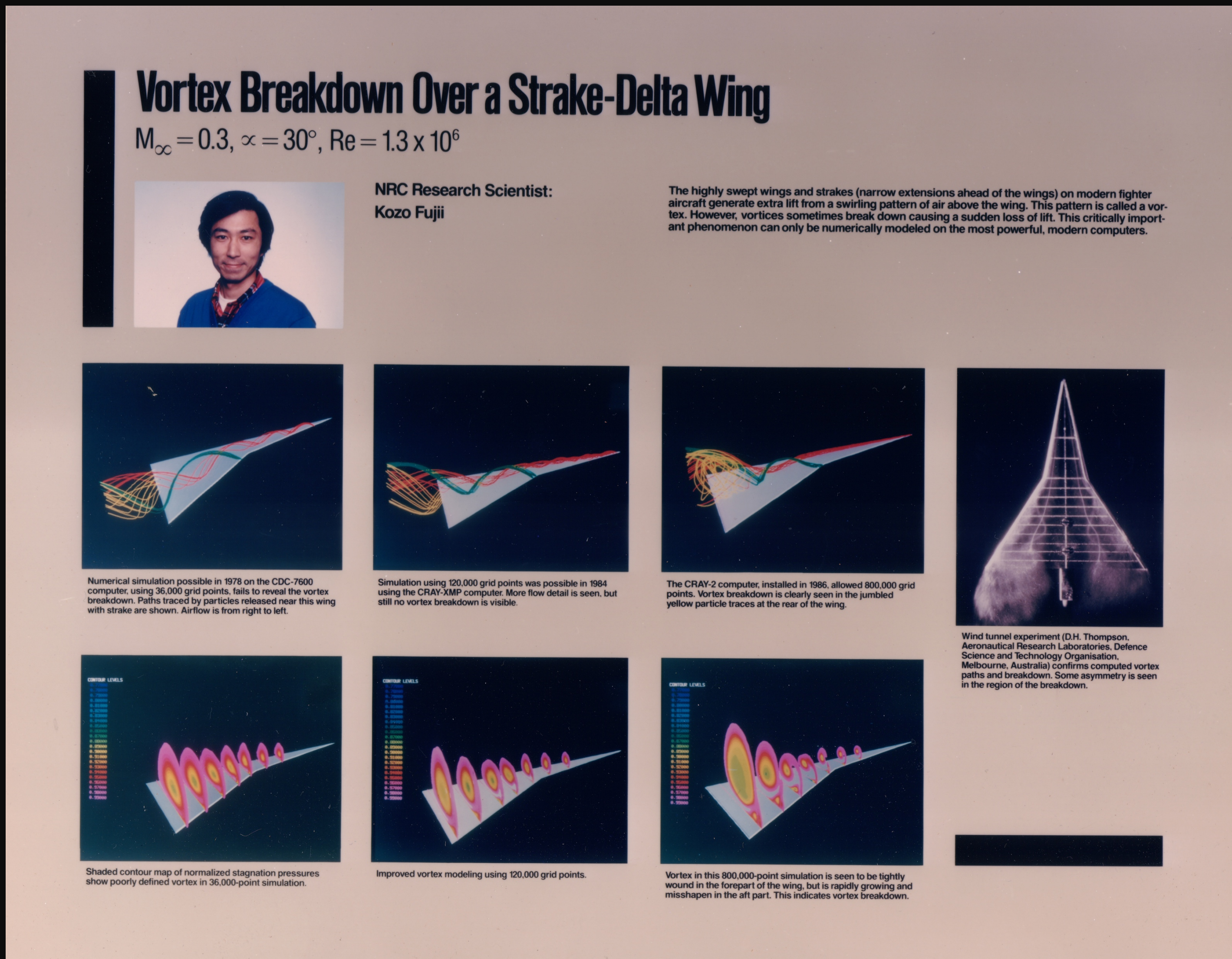
with many colleagues* and students**

Tokyo University of Science

Institute of Space and Astronautical Science, JAXA

JAPAN

Self Introduction

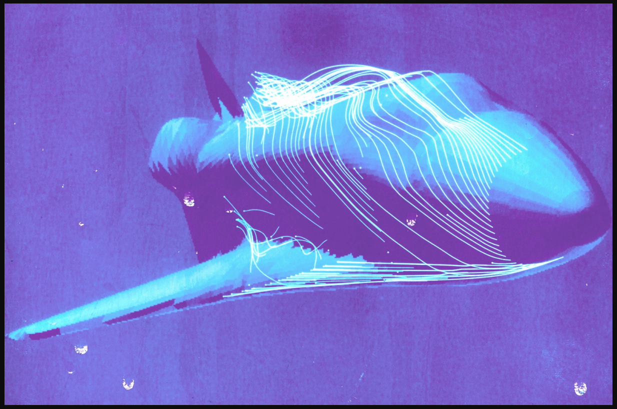


1986 at NASA Ames R. C.

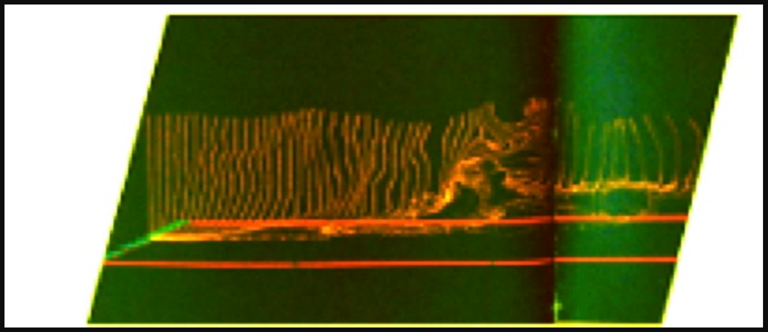
Outline

- History of CFD (in Aerospace) –my personal perspective
- Current status and recent changes
- Enabling technologies with HPC
  - Aeroacoustics with required predictability
    - High speed jets and rocket plumes
    - Rotating tires
  - Flow separation control as a product innovation
    - Plasma Actuator (DBD-PA)
    - Synthetic Jets
- Summary

CFD Simulations at NASA Ames R. C. in Early 1980's



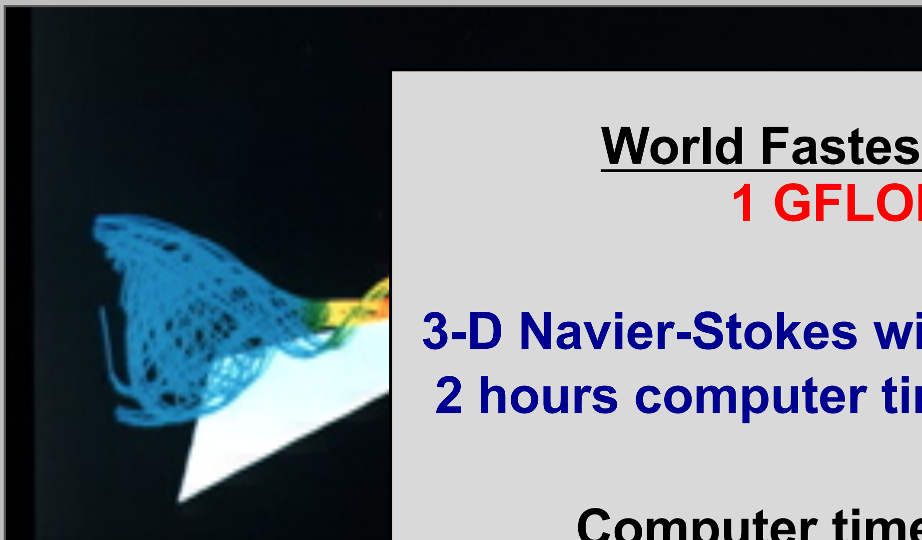
Practical Simulation
(Y. Rizk NASA Ames R. C.)

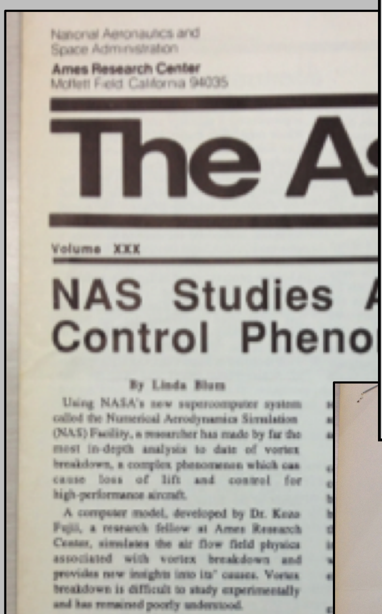


Simulation of basic turbulence
(P. Moin & J. Kim NASA Ames R. C.)

From NASA Website etc.

LESV over a Strake Delta Wing





National Aeronautics and Space Administration
Ames Research Center
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The A

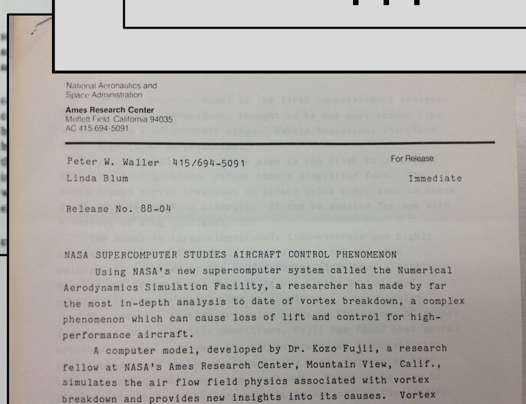
Volume XXX

NAS Studies A
Control Pheno

By Linda Blum

Using NASA's new supercomputer system called the Numerical Aerodynamics Simulation (NAS) Facility, a researcher has made by far the most in-depth analysis to date of vortex breakdown, a complex phenomenon which can cause loss of lift and control for high-performance aircraft.

A computer model, developed by Dr. Kozo Fujii, a research fellow at Ames Research Center, simulates the air flow field physics associated with vortex breakdown and provides new insights into its causes. Vortex breakdown is difficult to study experimentally and has remained poorly understood.



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Peter W. Waller 415/694-5091 For Release
Linda Blum Immediate

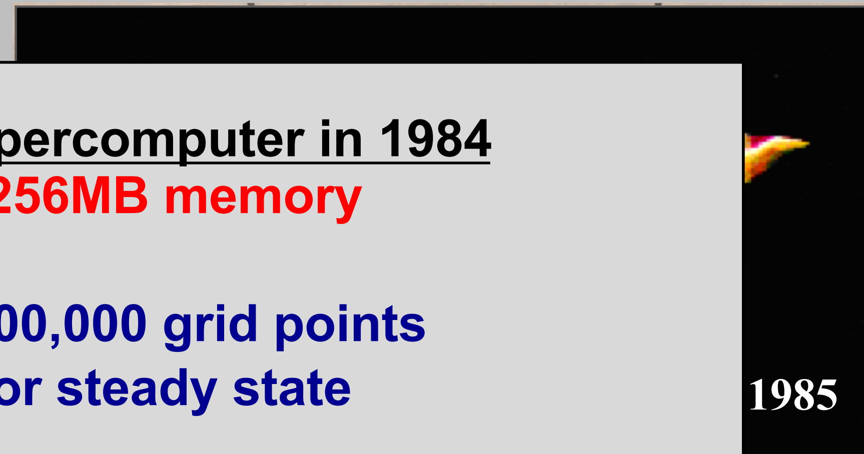
Release No. 88-04

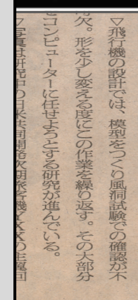
NASA SUPERCOMPUTER STUDIES AIRCRAFT CONTROL PHENOMENON

Using NASA's new supercomputer system called the Numerical Aerodynamics Simulation Facility, a researcher has made by far the most in-depth analysis to date of vortex breakdown, a complex phenomenon which can cause loss of lift and control for high-performance aircraft.

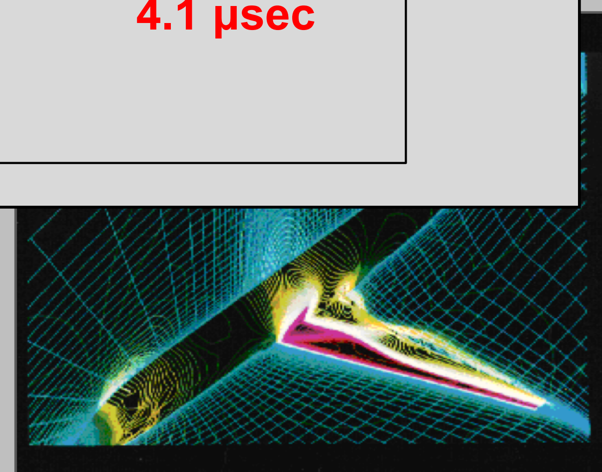
A computer model, developed by Dr. Kozo Fujii, a research fellow at NASA's Ames Research Center, Mountain View, Calif., simulates the air flow field physics associated with vortex breakdown and provides new insights into its causes. Vortex

Transonic flows over a practical wing





飛行機の設計では、模型をつくり風洞試験での確認が不可欠。形を少し変える度にこの作業を繰り返す。その大部分をコンピューターに任せようとする研究が進んでいる。



World Fastest Supercomputer in 1984

1 GFLOPS, 256MB memory

3-D Navier-Stokes with 200,000 grid points

2 hours computer time for steady state

Computer time/grid/iteration

1983	CRAY 1	86.0 µsec
1985	FJT VP400	6.7 µsec
1986	CRAY 2	20.0 µsec
2007Pen	Xeon (3.2GHz)	4.1 µsec
	. . .	
	. . .	

Two Supporting Factors for CFD Progress

- **Computer progress: 1000 times faster/every 10 years**
  (Environment in Japan as an example)

1985	Fujitsu VP400 :	1 GFLOPS performance,	256MB memory
2011	K computer :	10 PFLOPS performance,	>1 PB memory
2020+	Post K computer :	~1 EFLOPS performance,	? memory

- **Numerical algorithm progress: 10 - 500 times faster/ every 10 years**

（1）Efficient time integration scheme : RK, LU, LU-SGS, ADI-SGS,...

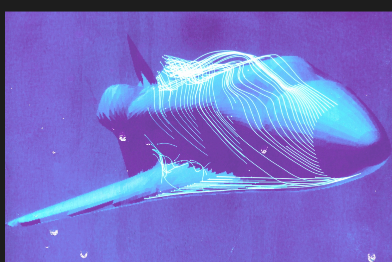
（2）Improve spatial resolution : CD, WENO, WCNS, FR,...

One example from CP, and

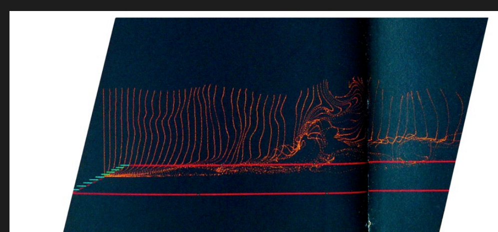
New Stage of CFD Simulations

Early to middle 1980's

CRAY-1S
(80-120MFLOPS)



Practical Application using RANS model

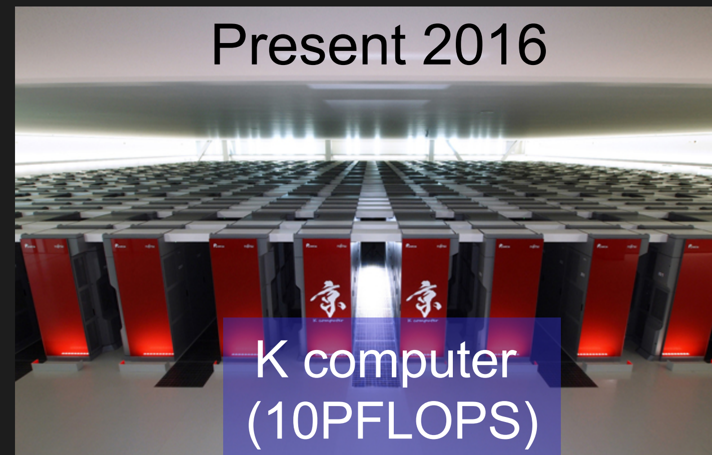


Basic Turbulence Research

From NASA Website etc.

15% of the resource goes to industrial use

Present 2016



K computer
(10PFLOPS)

\+

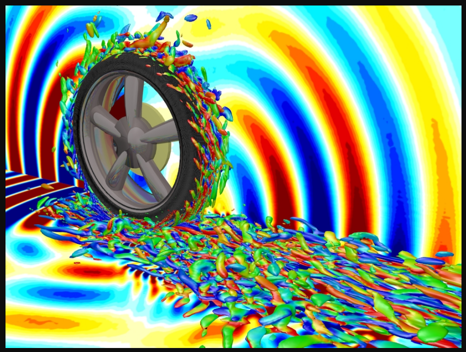
Compact and other schemes

High fidelity Simulations using LES

Innovation?

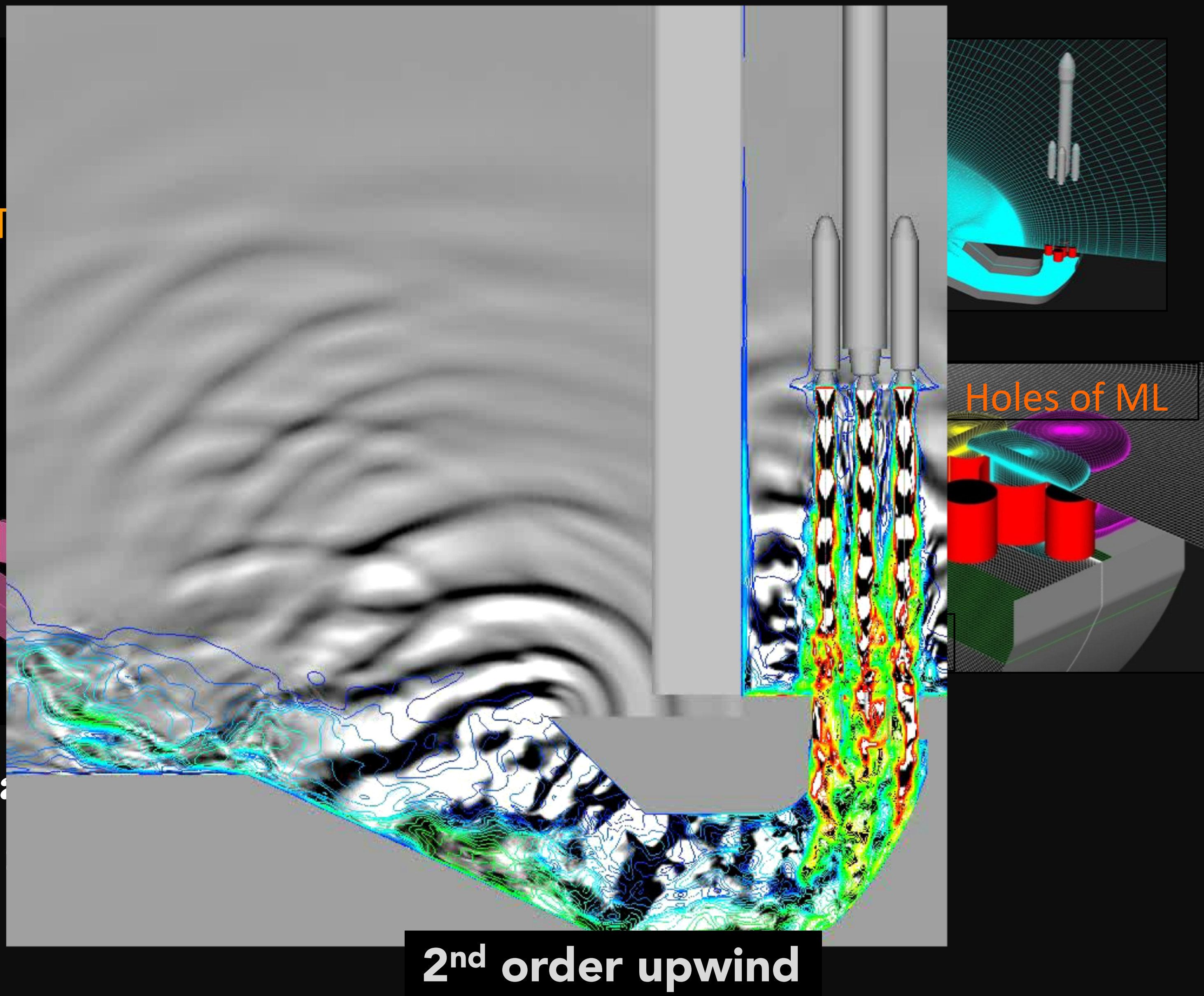
Enabling technologies with HPC -1

(1) Aeroacoustics with required predictability



* All the simulations from here were carried out with 6th order compact differencing unless with special notation

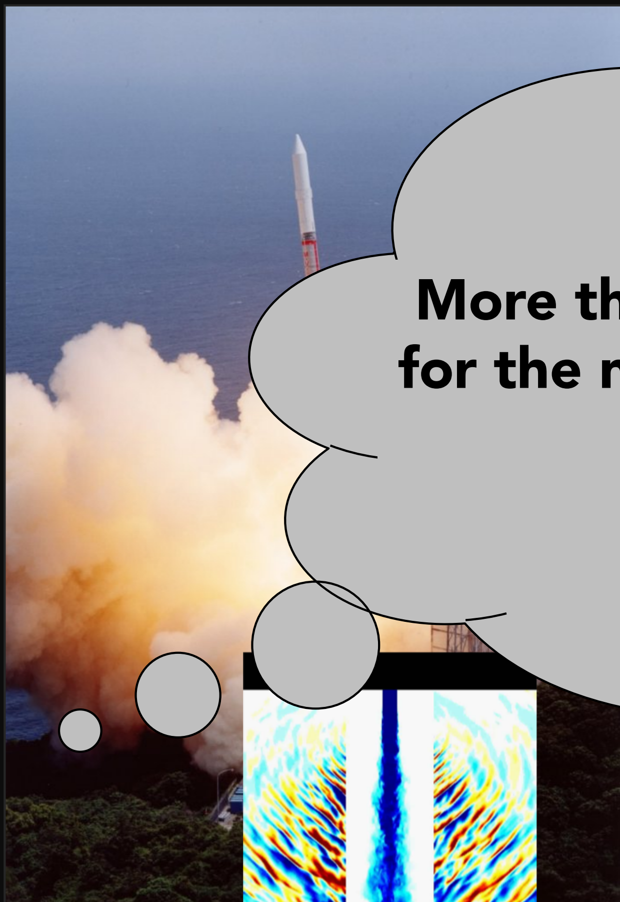
H-IIA Launch

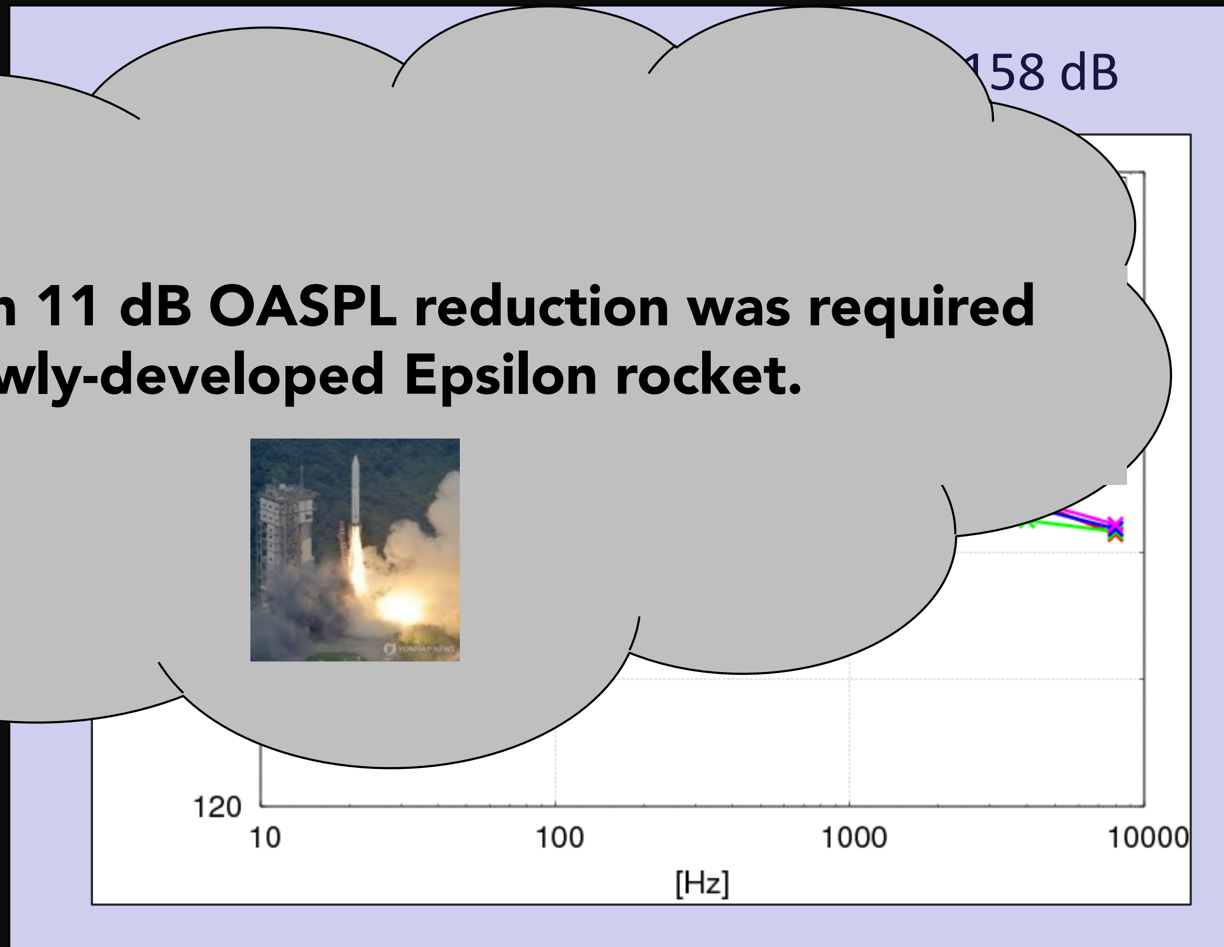


- Overset zon
- Grid points

Tsutsumi, S., Takaki, R., Shima, E., Fujii, K., and Arita, M. AIAA 2008-390, Jan. 2008

Plume Acoustics for the former M-V Rocket





More than 11 dB OASPL reduction was required for the newly-developed Epsilon rocket.

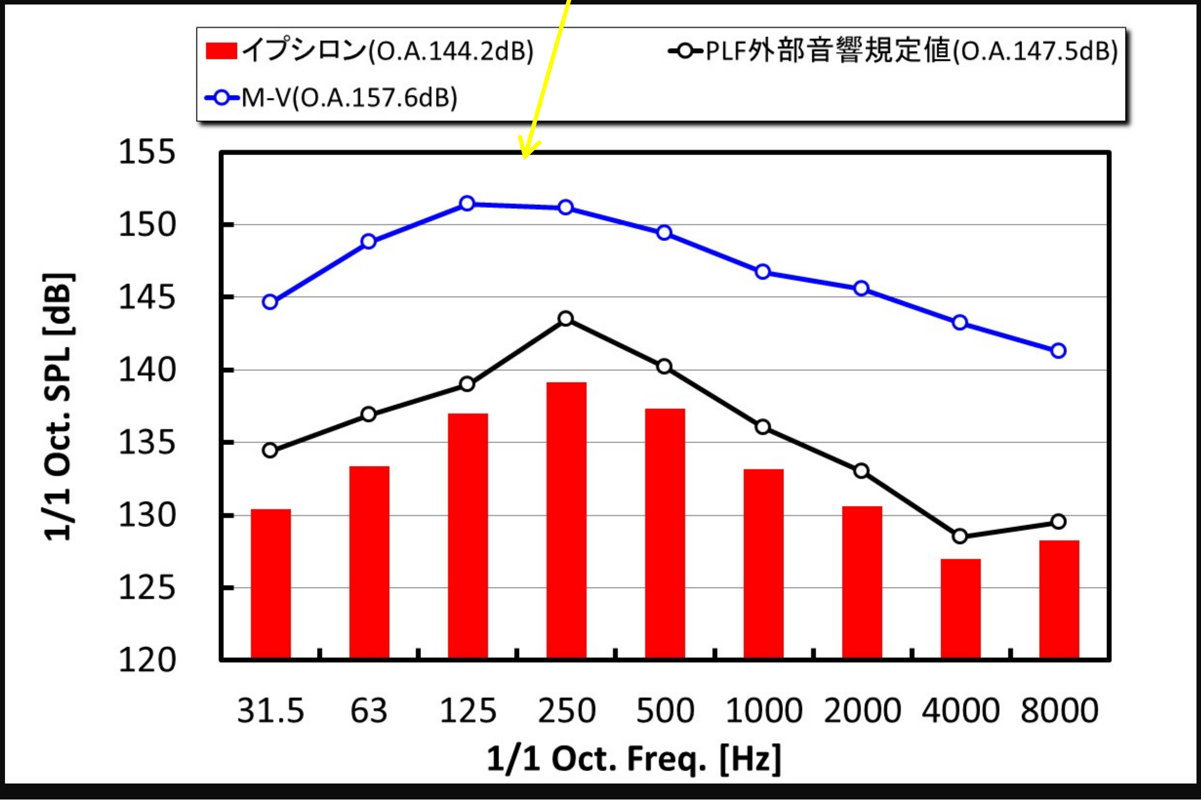
M-V r h

140dB　2.0×10^{-3}
100dB　2.0×10^{-5}
20dB　2.0×10^{-9}

6dB低減で1/2，10dB低減は1/4，20dB低減は1/10

Plume Acoustics for Newly Developed Epsilon Rocket

13dB (OASPL) reduction



- **3 dB reduction by the size effect**
- **10 dB reduction (OASPL) by the new launch complex**

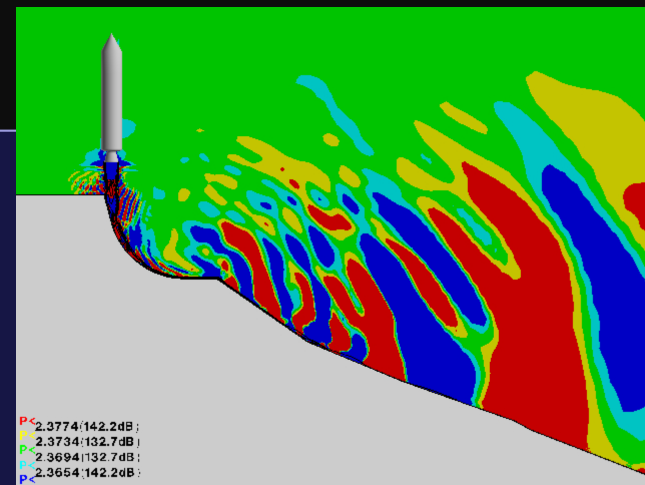
* This study was mainly conducted by Dr. S. Tsutsumi at JEDI center/JAXA

How did we reduced the SPL of Epsilon rocket ?

Flame Deflector

Flame Duct

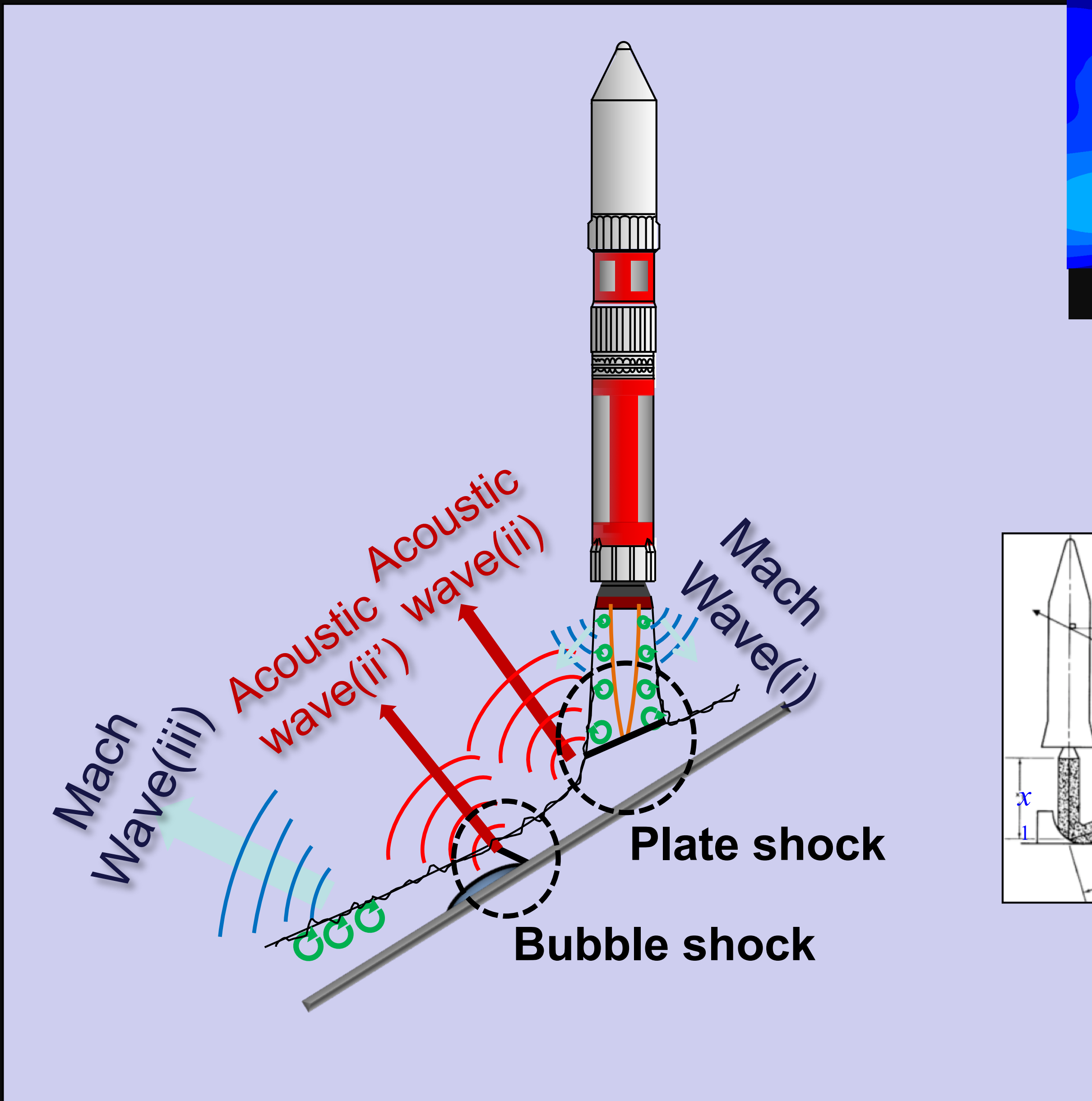
Launch Deck

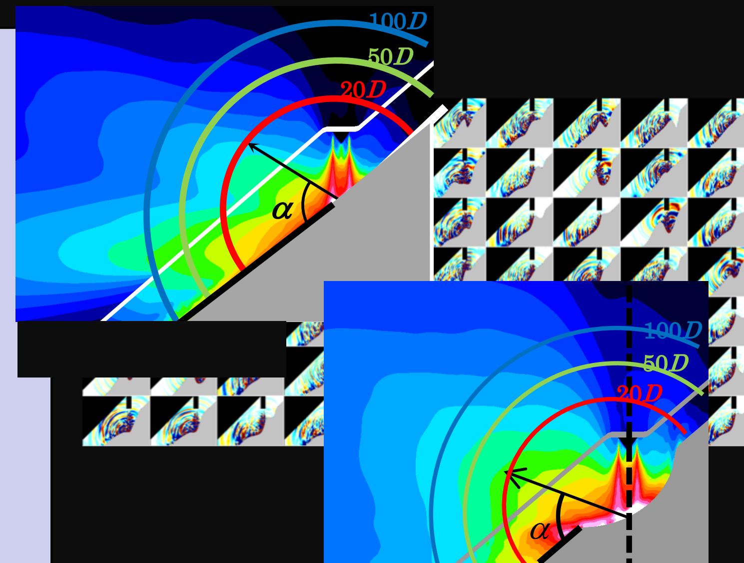


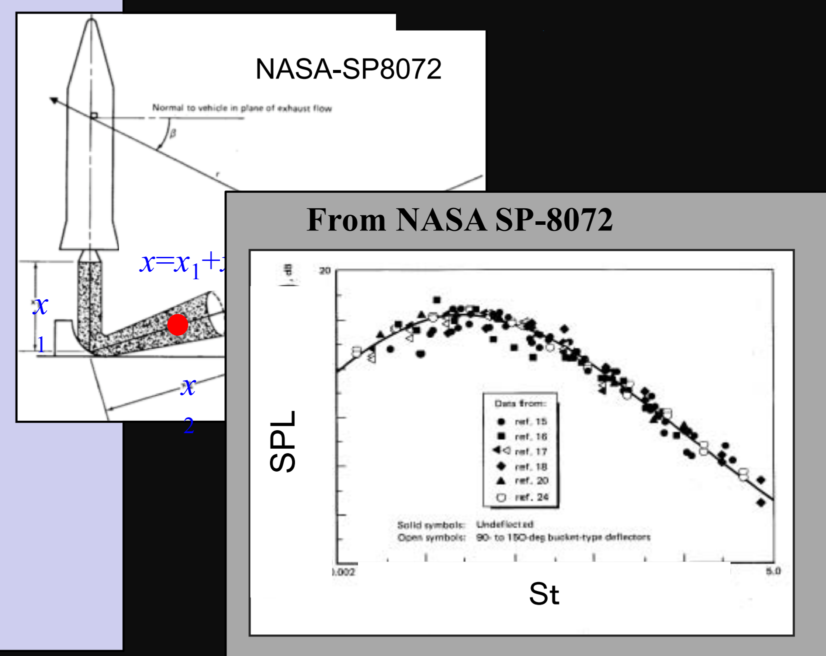
2nd order upwind

This study was mainly conducted by Dr. S. Tsutsumi at JEDI center/JAXA

Detection of Sound Sources





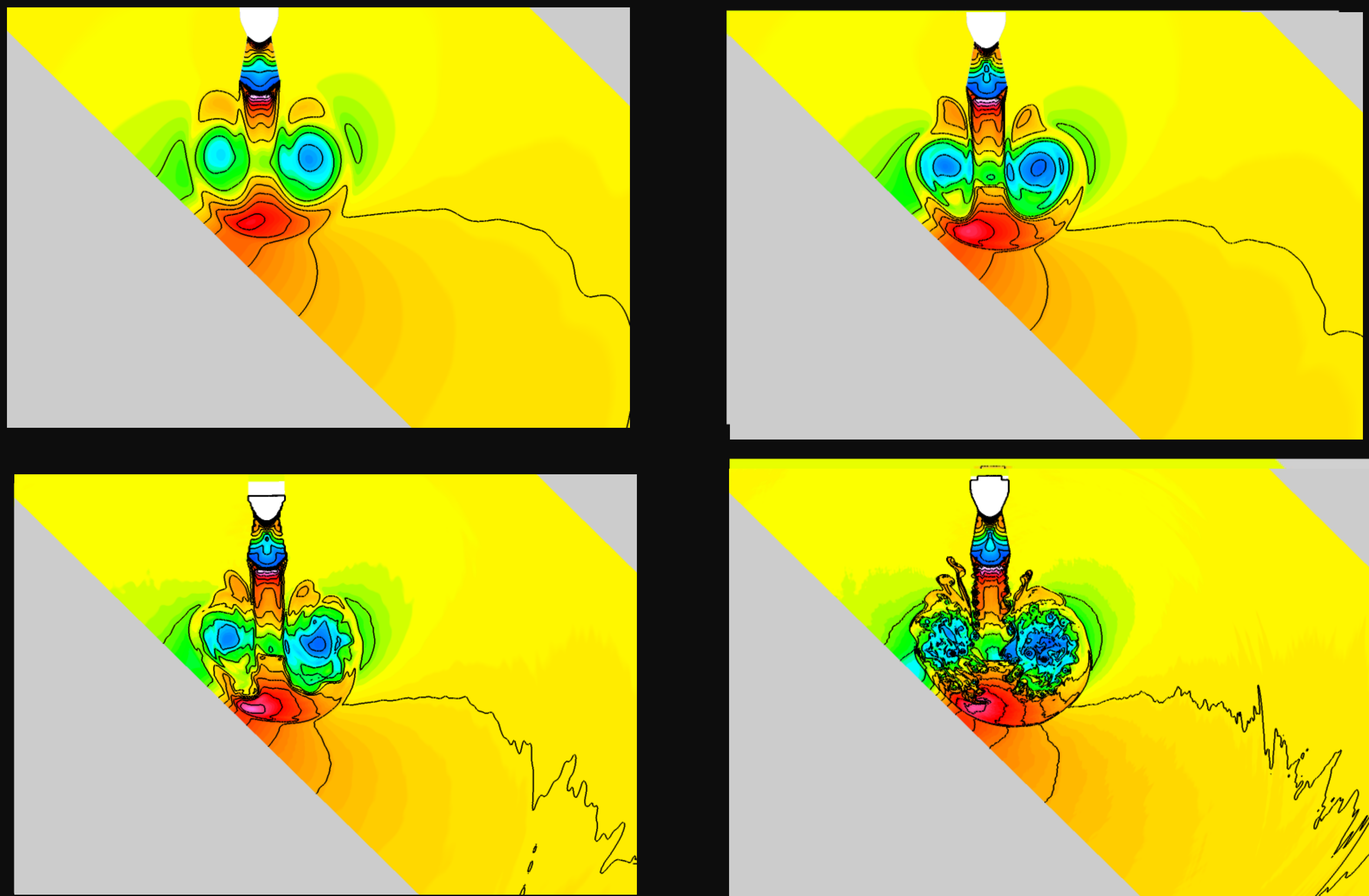


NASA/JAXA CFD Research Collaboration for Rocket Launching Aero. Problems

Nonomura, T. et al. ICCFD7-3103, 2012

2nd order MUSCL/FDS

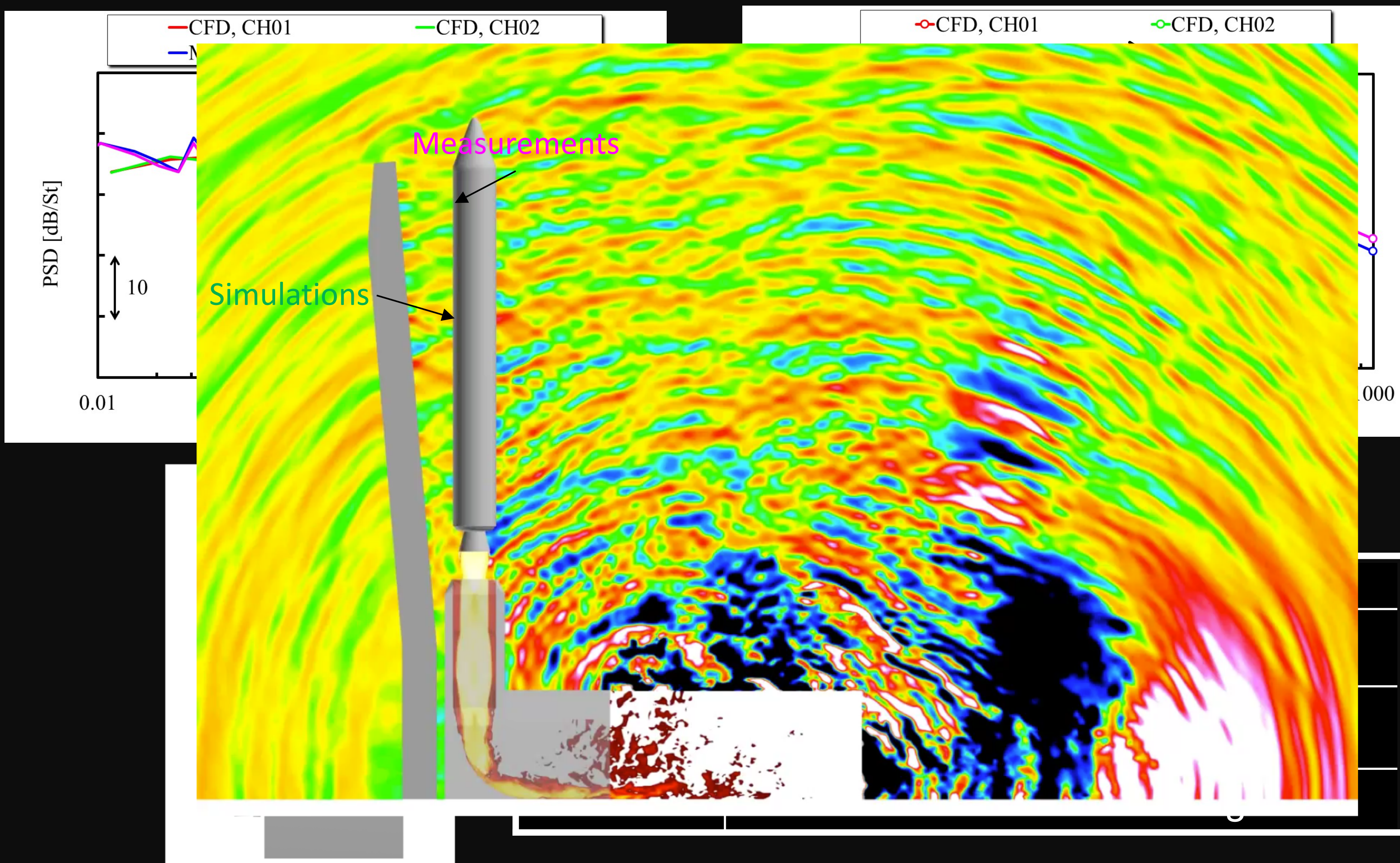
7th order WCNS



Coarse Grid (0.165M)

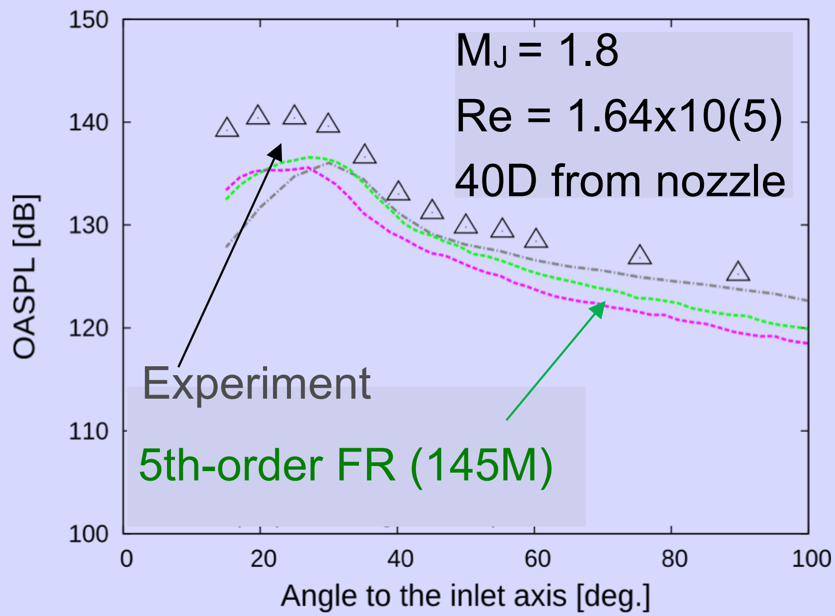
Fine Grid **(2M)**

Post Flight Simulations with a High order Scheme

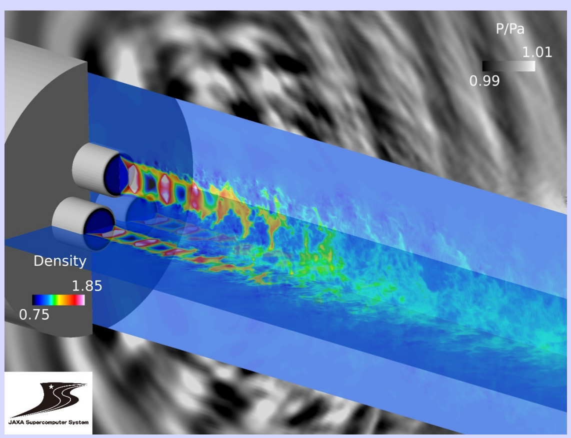


Tsutsumi, S. et al. "Assessing Prediction and Reduction Technique of Lift-off Acoustics Using Epsilon Flight Data," AIAA Paper 2015-1007.

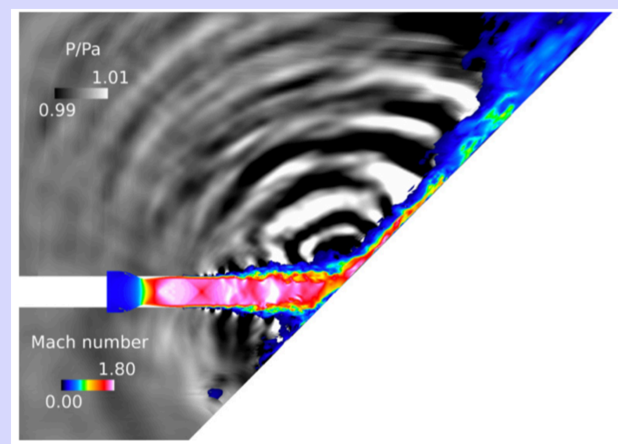
LES of rocket plume acoustics using FR/CPR method



Cluster rocket



Impinging jet on flat plate (p2)



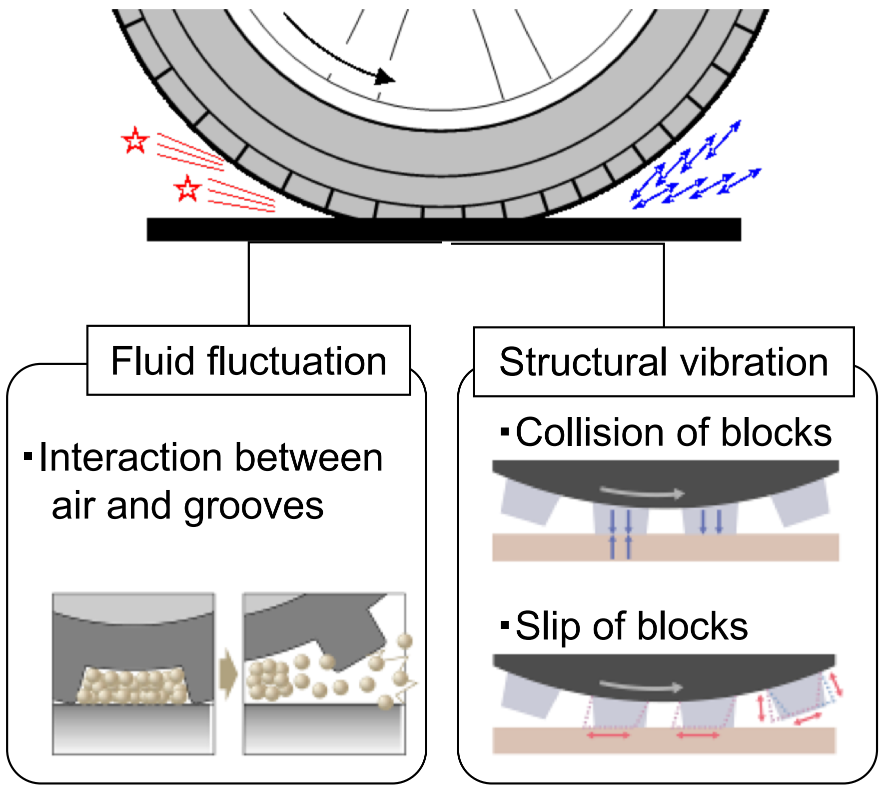
T. Haga et al., AIAA 2015-0831; T. Haga, et al., 30th ISTS, Vol. 2015-o-2-13, 2015

Correction procedure via reconstruction

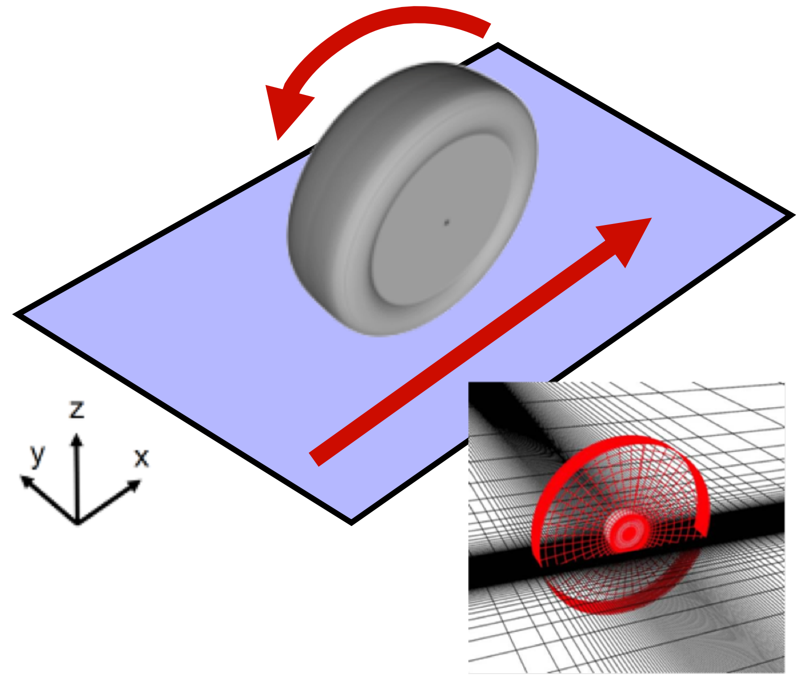
Background for Rotating Tire Simulations

Regulation of tire noise will become effective on 2018/4 in Japan

Mechanism of tire noise



Courtesy of Dr. M. Koishi, Yokohama Rubber Co. Ltd.



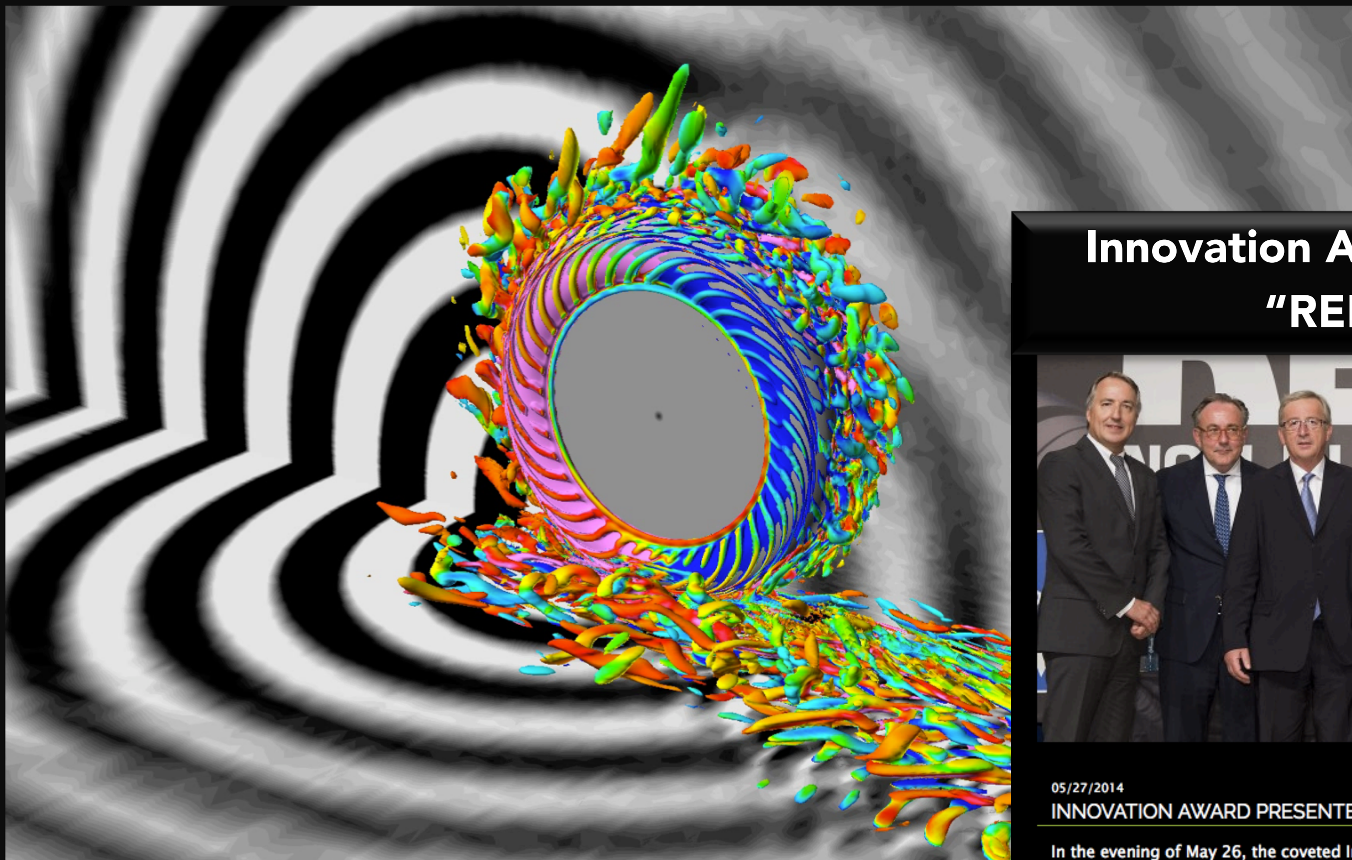
- Tire Size : 215/55R17
- Diameter of tire：0.6 [m]
- Traveling speed：122 [km/h]

SCALE: 10% of real models

* One hundred million grid points

Collaboration with Yokohama Rubber Co. Ltd.

Aeroacoustics from a Rotating Tire



Innovation Award in Tire Messe "REIFEN 2014"

05/27/2014

INNOVATION AWARD PRESENTED AT MESSE ESSEN

In the evening of May 26, the coveted Innovation Award was presented at Messe Essen during the ceremonial opening of Reifen 2014. The manufacturers of the best new products for the tyre sector are honoured with the mark of distinction.

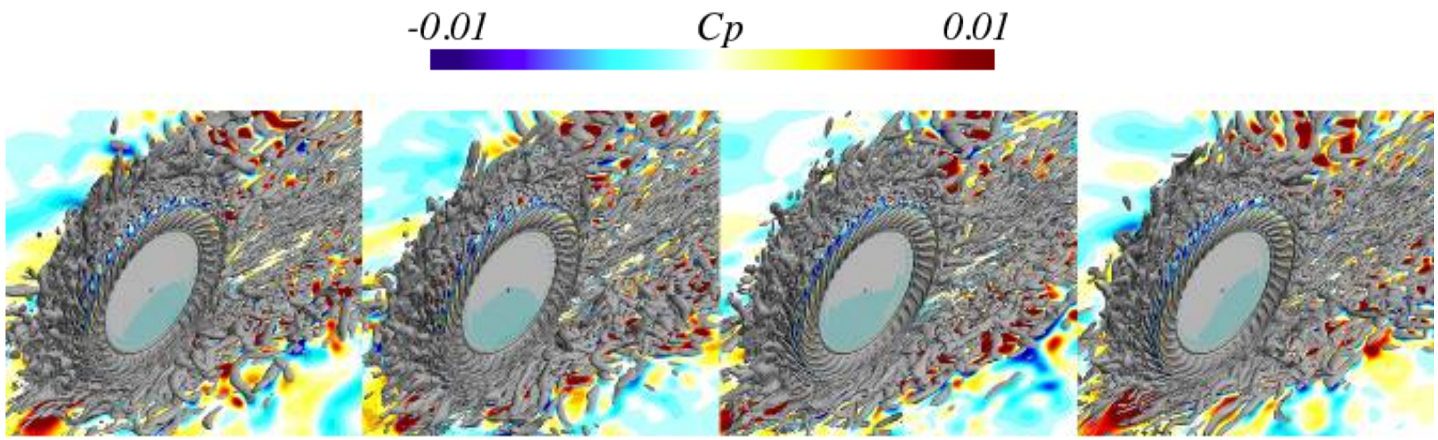
From outer space into the garage: In the "Technology and Products" category, the Japanese tyre manufacturer Yokohama convinced the jurors with a process for the visual representation of the aerodynamic and acoustic rolling behaviour of tyres. Together with the Japanese space authority JAXA, the company thus managed to achieve a genuine breakthrough on the path to the development of quieter and aerodynamic tyres. The "Oscar" in the "Environmental and Resource Conservation" category went to the German manufacturer of alloy wheels Borbet: Its "NatureWheel" process is supplementing the traditional casting of alloy wheels with the utilisation of a natural mineral. That leads to a weight reduction with an unchanged strength.

Collaboration with Yokohama Rubber Co. Ltd.

Computer resource: NEC SX-9 & SX-ACE in Cyber Science Center at Tohoku University

Effect of Groove Width (as an example)

No groove | Standard groove width | twice the width of standard groove | 3 times the width of standard groove



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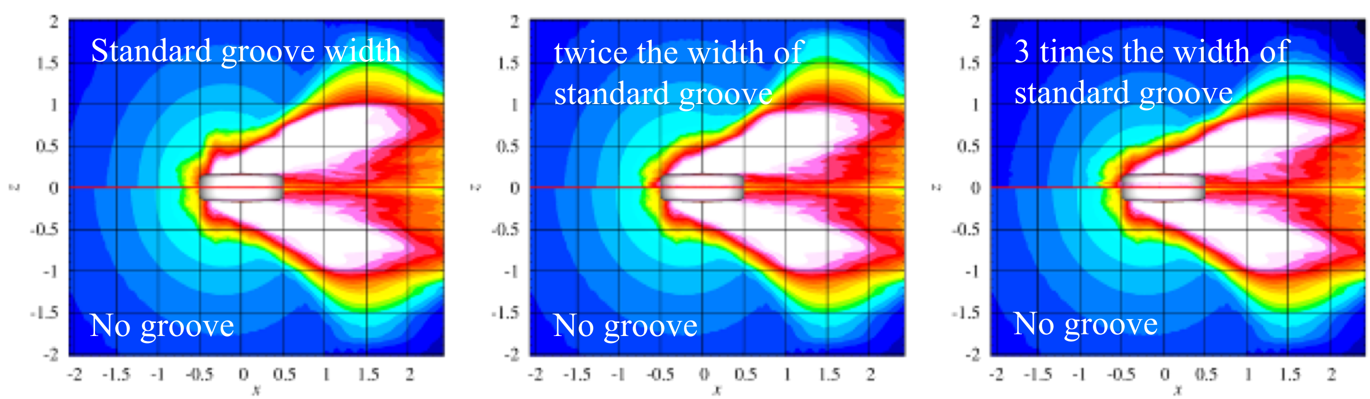
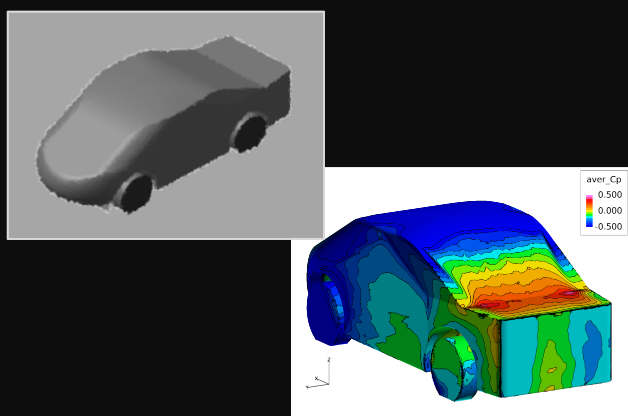
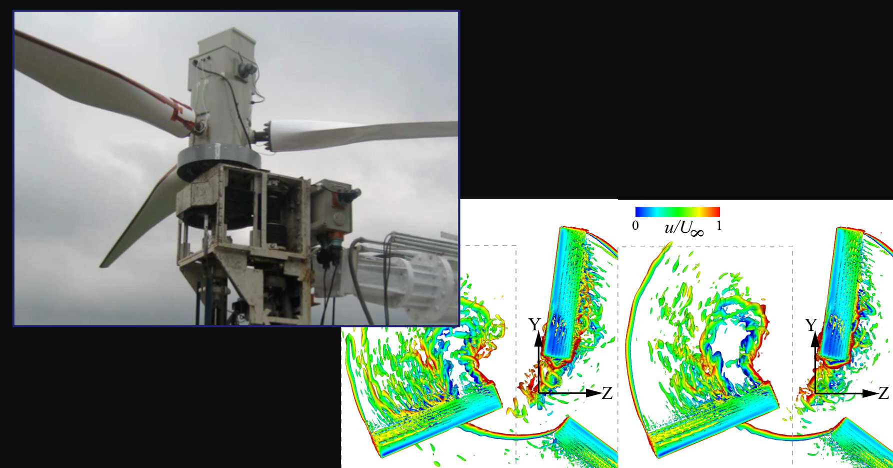


1381 [Hz]

Enabling technologies with HPC -2

(2) Flow control devices toward product Innovation





*** All the simulations from here were carried out with 6th order compact differencing unless with the special notation**

Achievemen... Status

- Simulati... feasibl...
- Good softw... ...ation, flow simulati...

Prof. Dean Chapman's Message in 1979

" There are two major motivations behind CFD. It would not change in coming decades."

(1) Providing an important new technology capability

- A lot of information both in time and space is obtained, which helps understanding of fluid physics

(2) Economics

- A new economical tool "CFD" in the aerodynamic design process

→ Consider difference of CFD simulations in 1985 and 2017?

My Guggenheim Lecture in ICAS2004

ICAS: International Congress of Aeronautical Sciences

IS CFD only the replacement of WT?

Fujii K., "Progress and Future Prospects of CFD in Aerospace –Wind Tunnel and Beyond," Progress in Aerospace Sciences, Vol. 41, No. 6, pp. 455-470, Elsevier, 2005.

My Guggenheim Lecture in ICAS2004

ICAS: International Congress of Aeronautical Sciences

CFD does more than WT!

CFD needs Evolutionary effort & Revolutionary effort

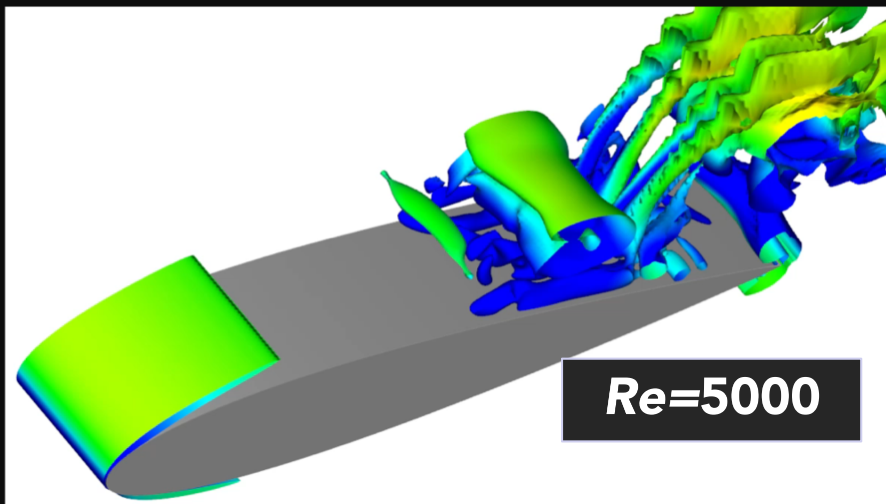
Revolutionary effort（Consider benefits of CFD)

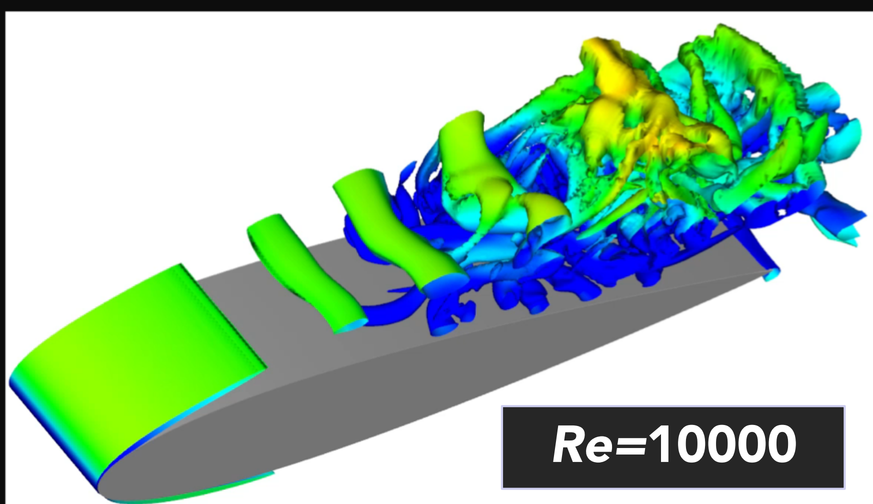
- Evaluation of scale effects
- Use CFD for new concepts

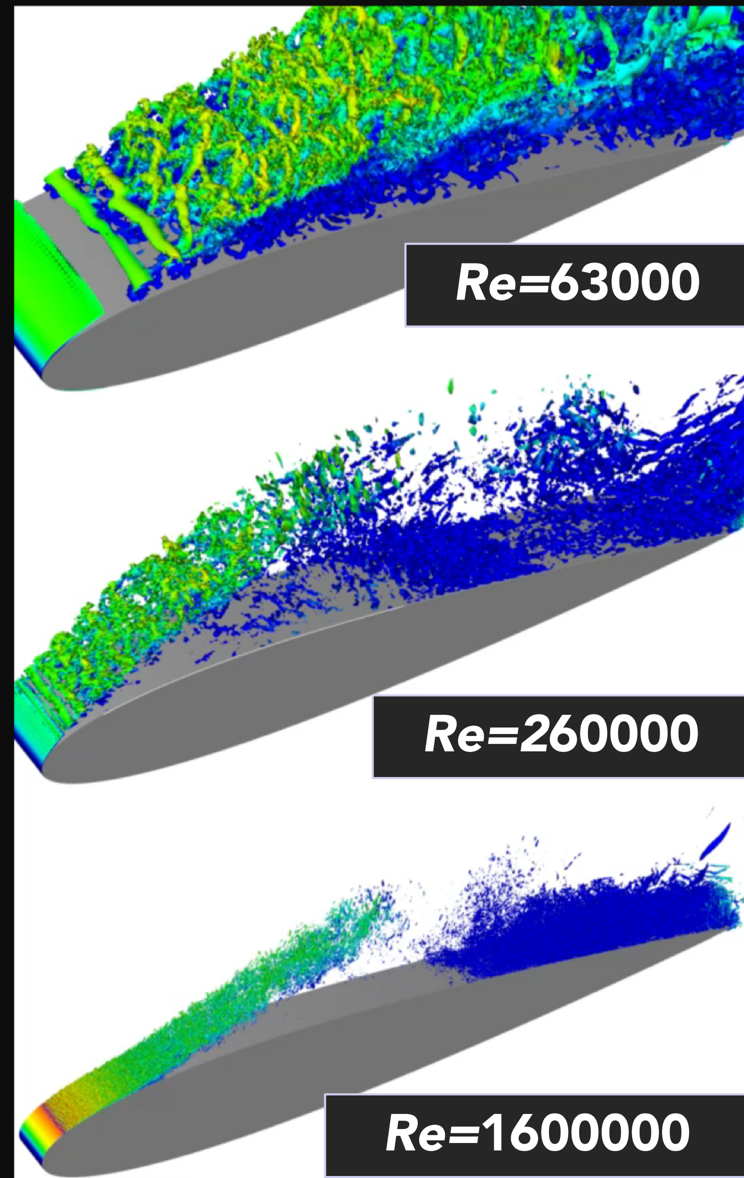
Fujii K., "Progress and Future Prospects of CFD in Aerospace – Wind Tunnel and Beyond," Progress in Aerospace Sciences, Vol. 41, No. 6, pp. 455-470, Elsevier, 2005.

Evaluation of Scale Effect

One of the important features required in high fidelity Simulations



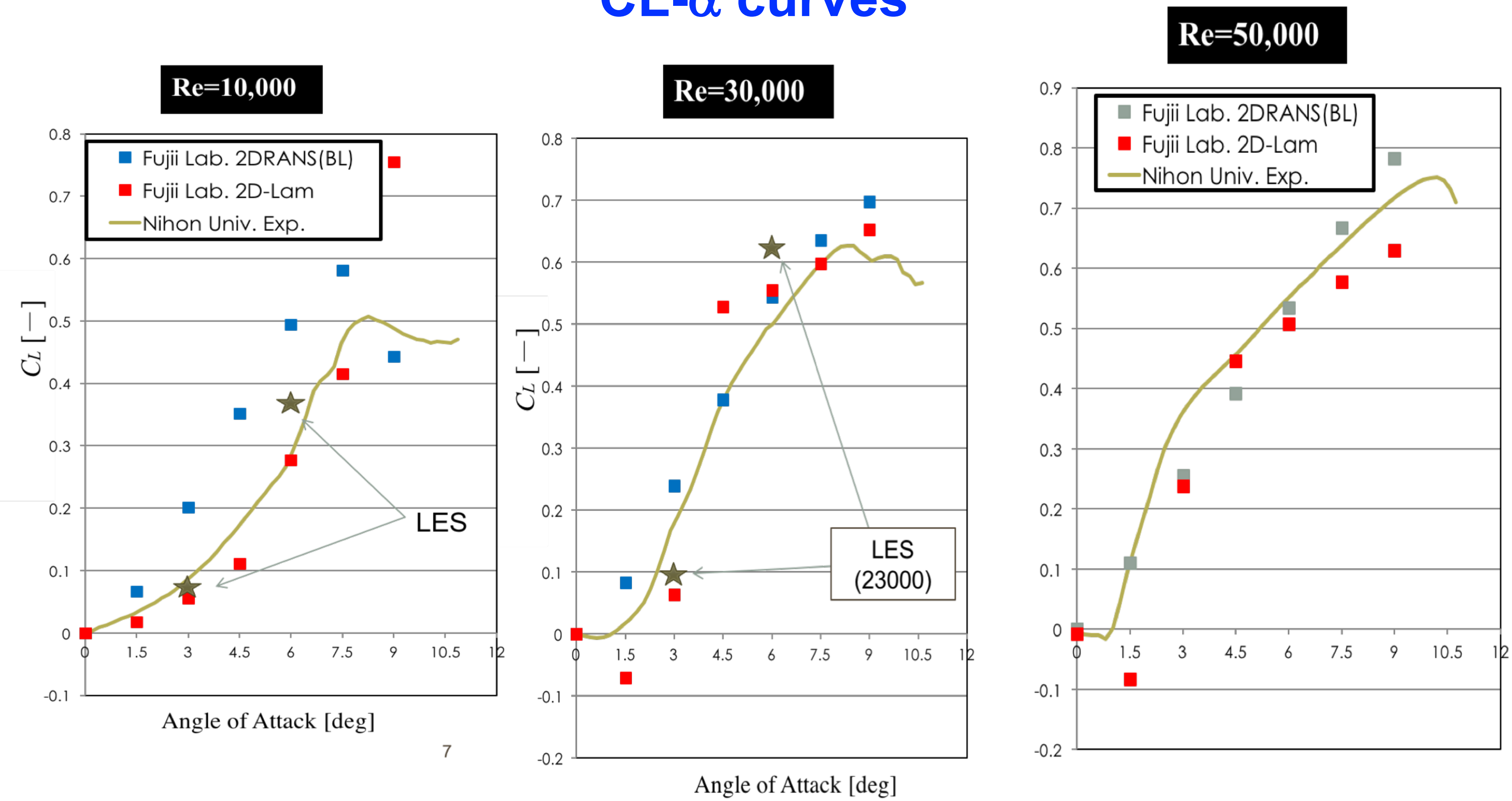




The other feature: applicability to wide variety of flow fields

Small change of Reynolds number changes flow features

CL-α curves



Low speed flows over NACA0012

D. Lee, K. Fujii, et al., J. Aircraft, Vol. 52, No. 1, pp. 296-306, 2015

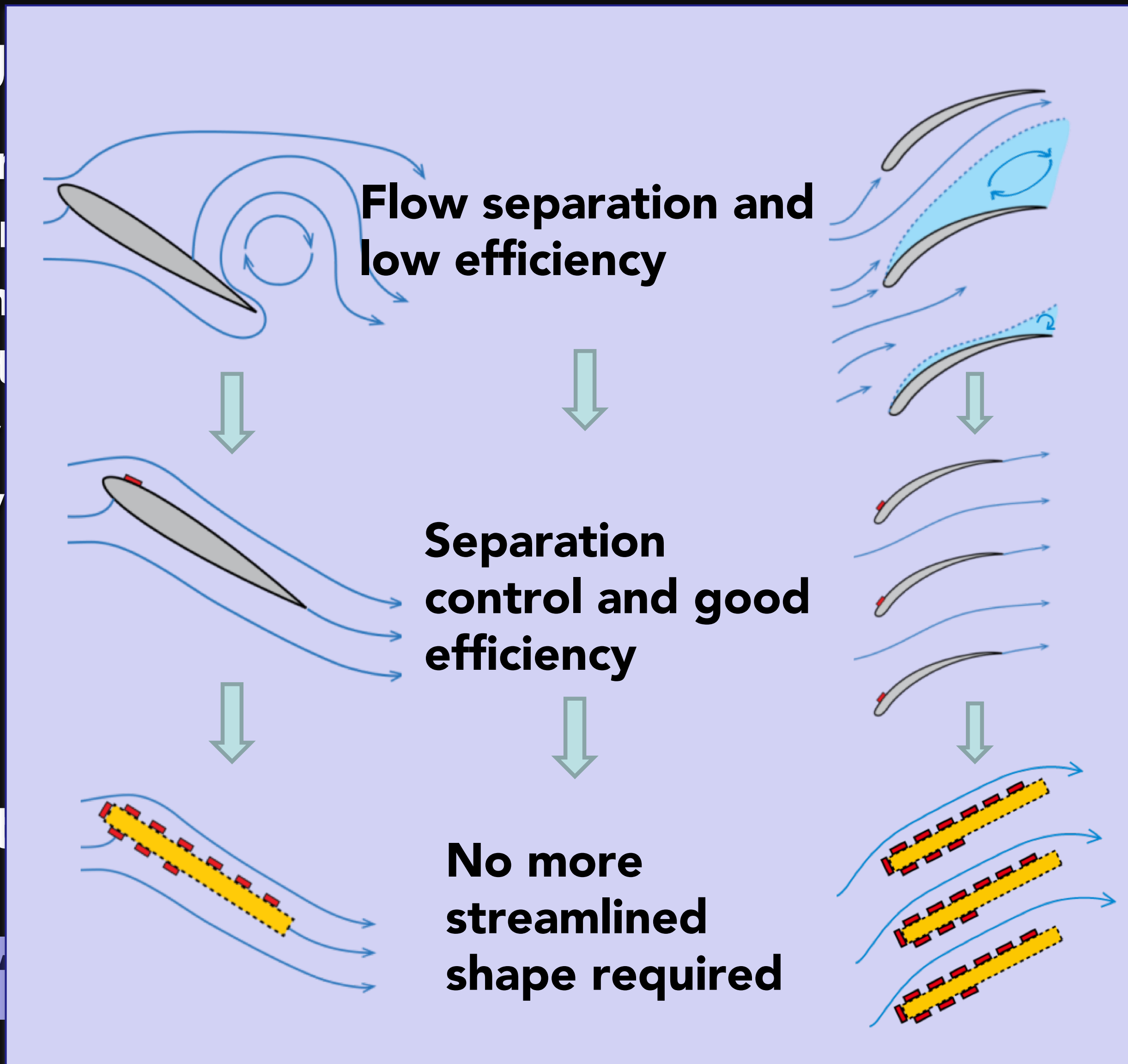
Our Product Innovation Project using K Supercomputer

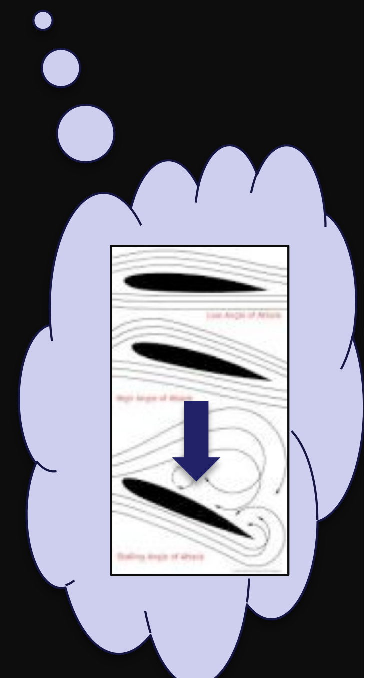
- **Backg**

Aerodynar … e of
body geor … the
aerodynar … ong
nonlinearit … as
deficiency … the
flows only

Event

From " … ices"



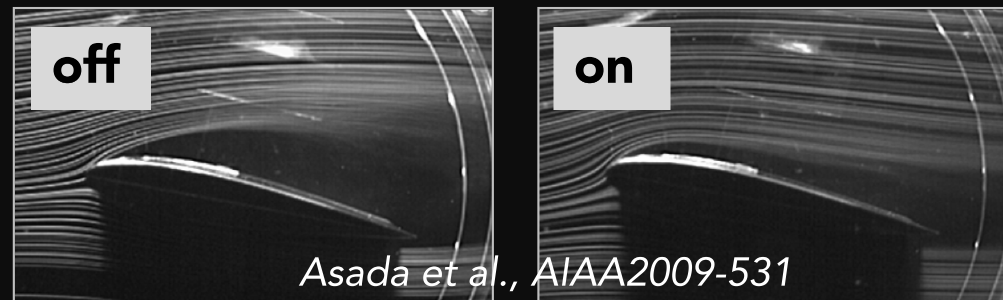


Another background: limit of geometry consideratoion

DBD Plasma Actuators for Airfoil Flows

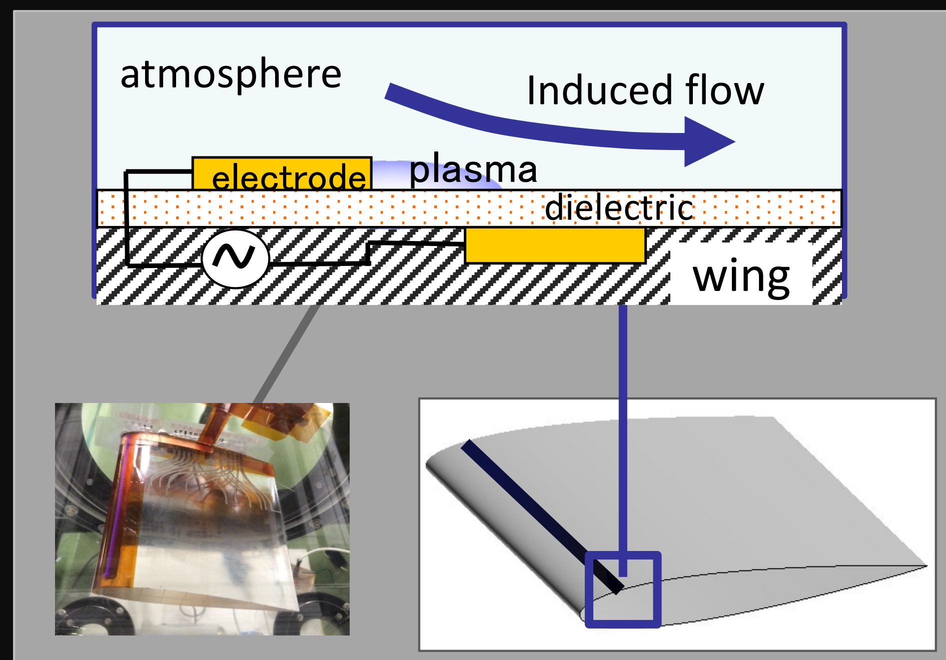
Common features of flow control by small/micro devices

- dynamic control
- Small device system
- Low energy consumption



DBD plasma actuator

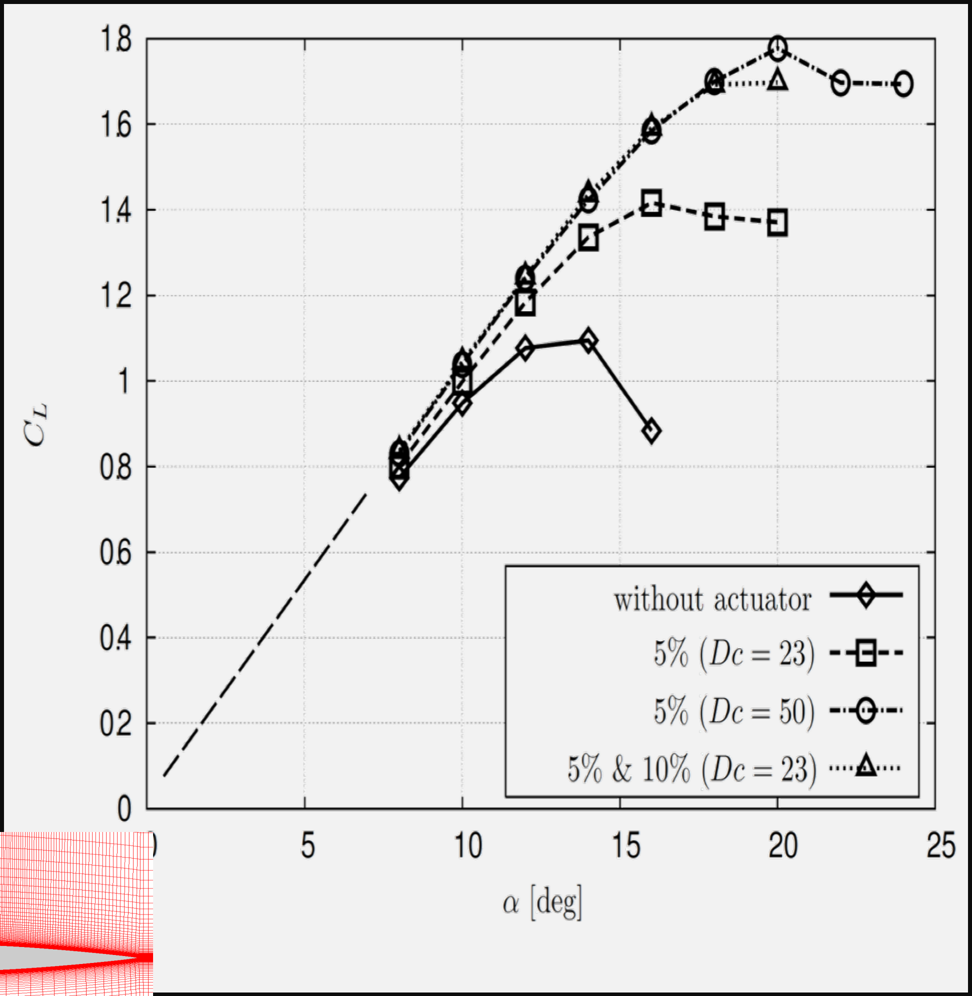
- Simple structure
- Additive system
- Good flow control authority

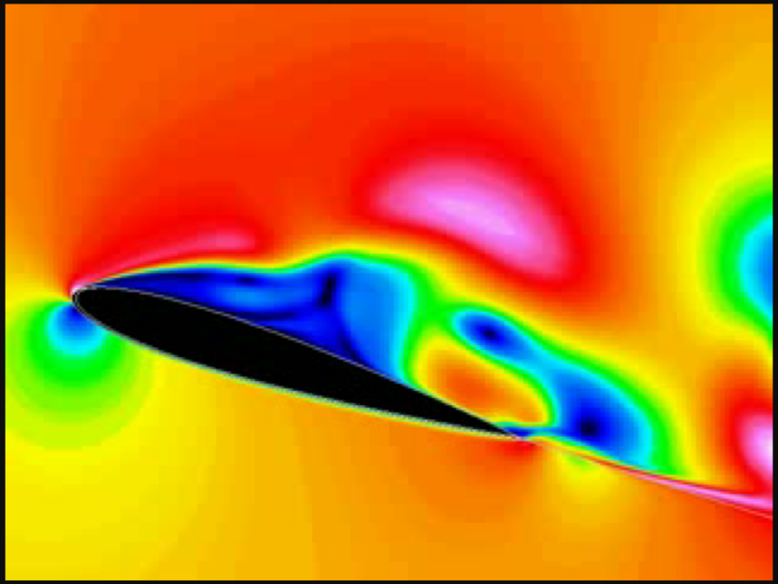


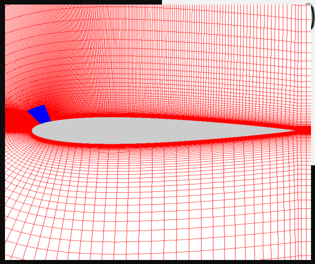
DBD plasma actuator on the airfoil

Our initial effort in 2007: Effect of DBD Plasma Actuator

CL-α Computed by 2D RANS

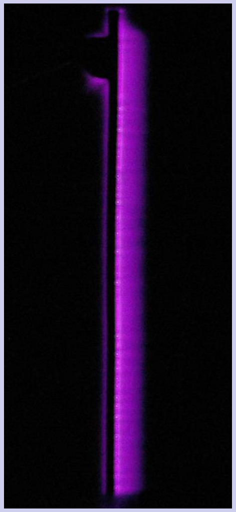


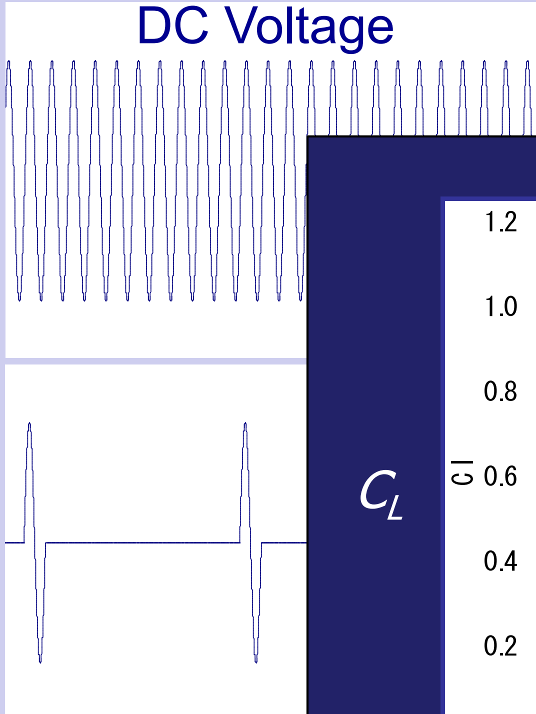


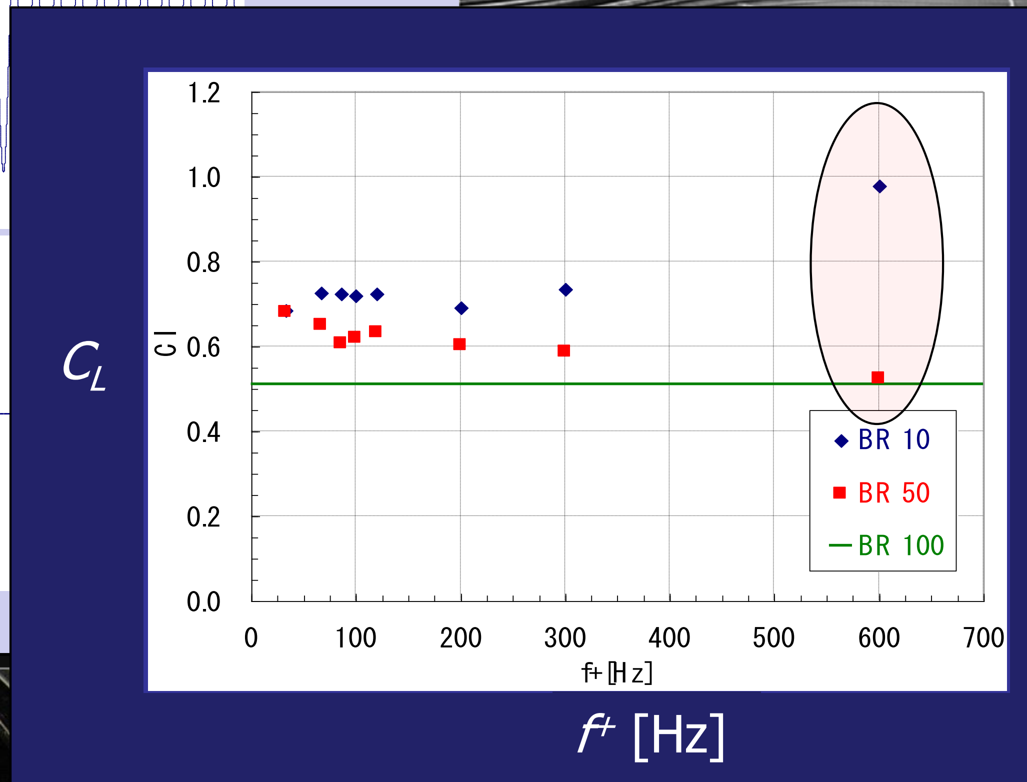


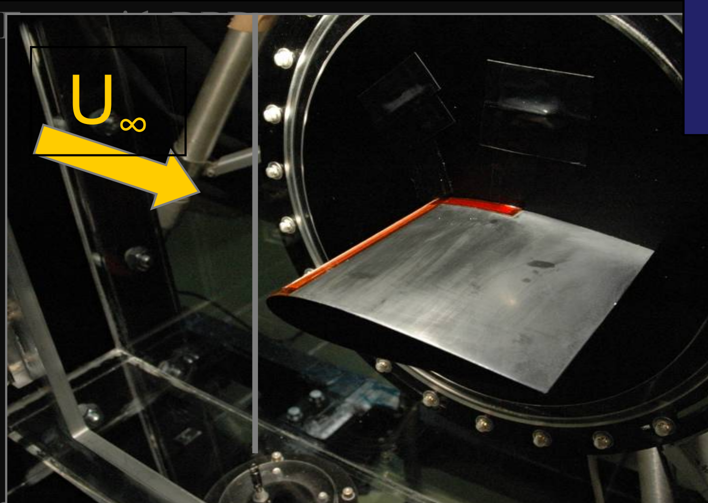
Tsubakino, Tanaka, and Fujii, AIAA 2007-0474

DBD Plasma Actuator in the Burst Mode









Burst frequency $$F^+ = \frac{f^+ c}{u_\infty}$$

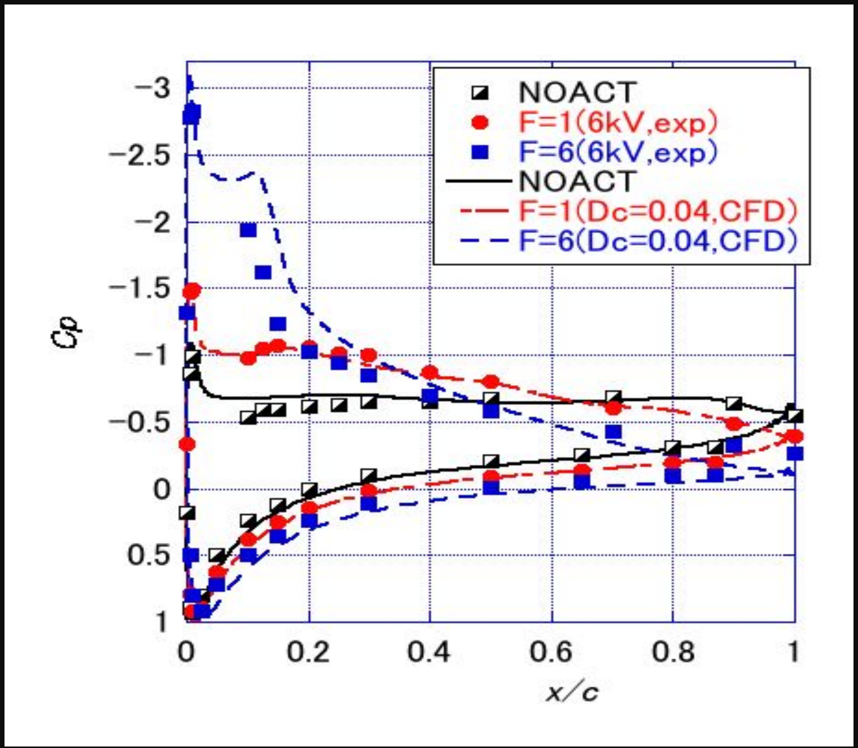
Asada, Ninomya and Fujii, AIAA Paper 2009-531

Computed Averaged Flow Field

Aerodynamic Characteristics (α = 12 deg.)

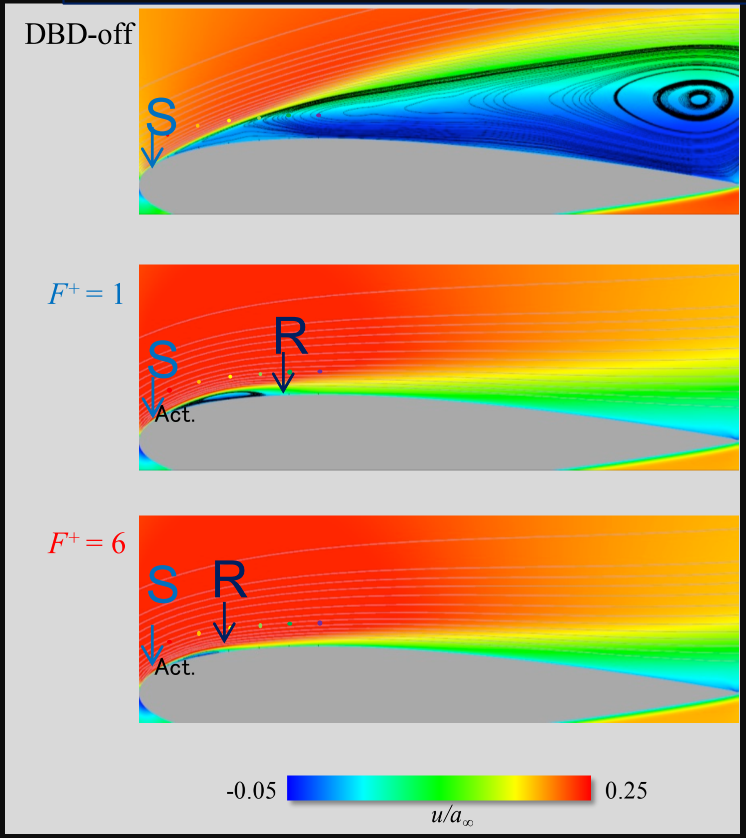
	C_L	C_D	C_{Dp}	C_{Df}	L/D
off	0.427	0.151	0.144	0.007	2.822
$F^+= 1$	0.842	0.069	0.059	0.010	12.168
$F^+= 6$	0.895	0.058	0.049	0.010	15.495

Cp Distributions



Time-averaged flow fields

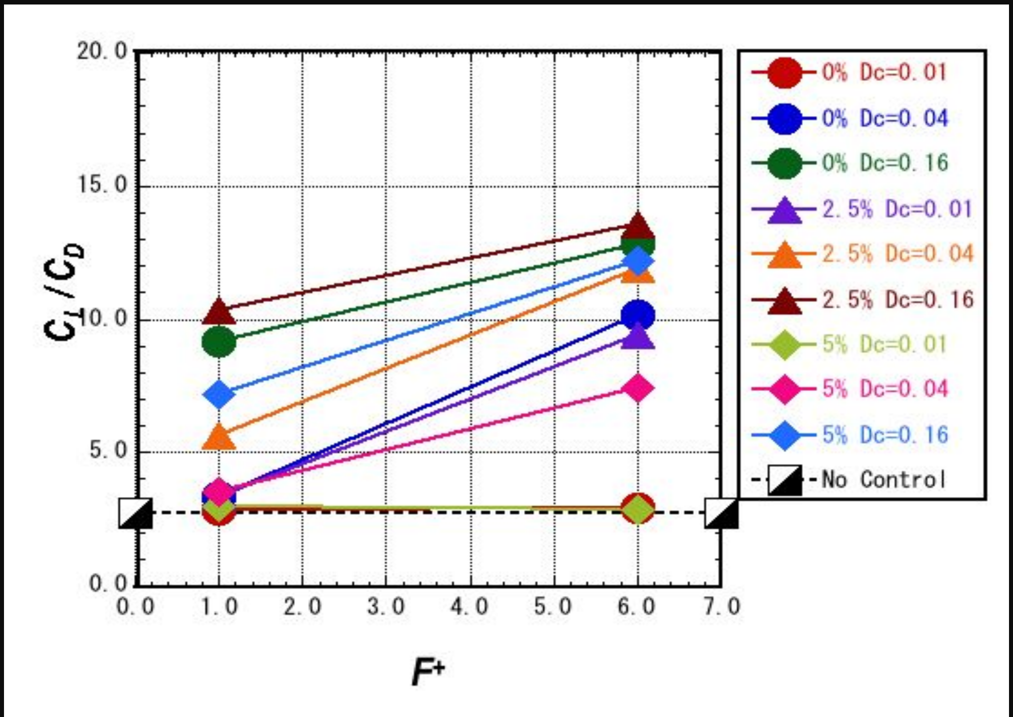
S:sep. pts. R: reattach. pts.



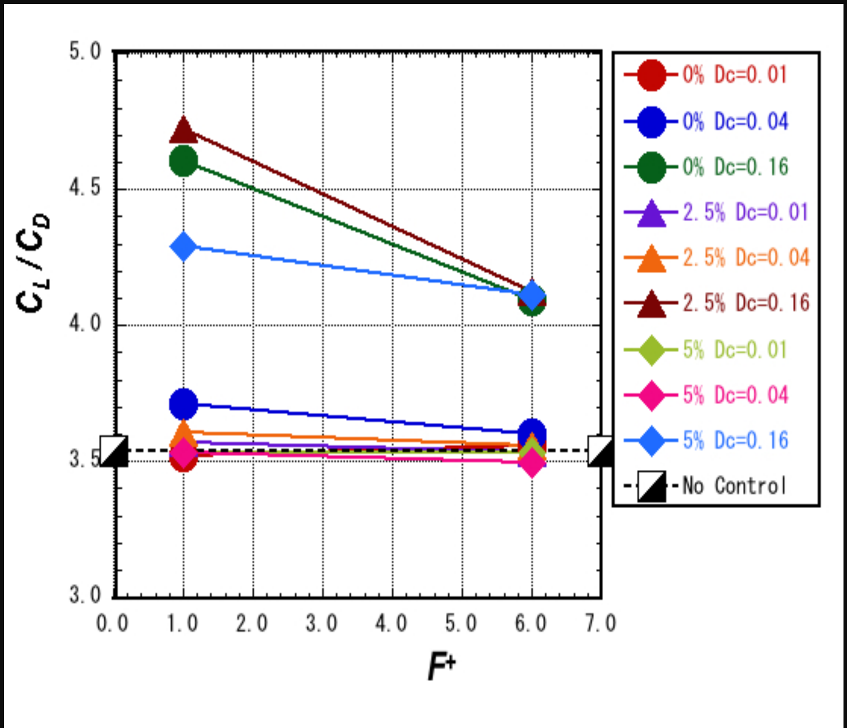
Chordwise velocity

Effect of Burst Frequencies

NACA0015, α = 14 deg., Re = 63,000



NACA0015

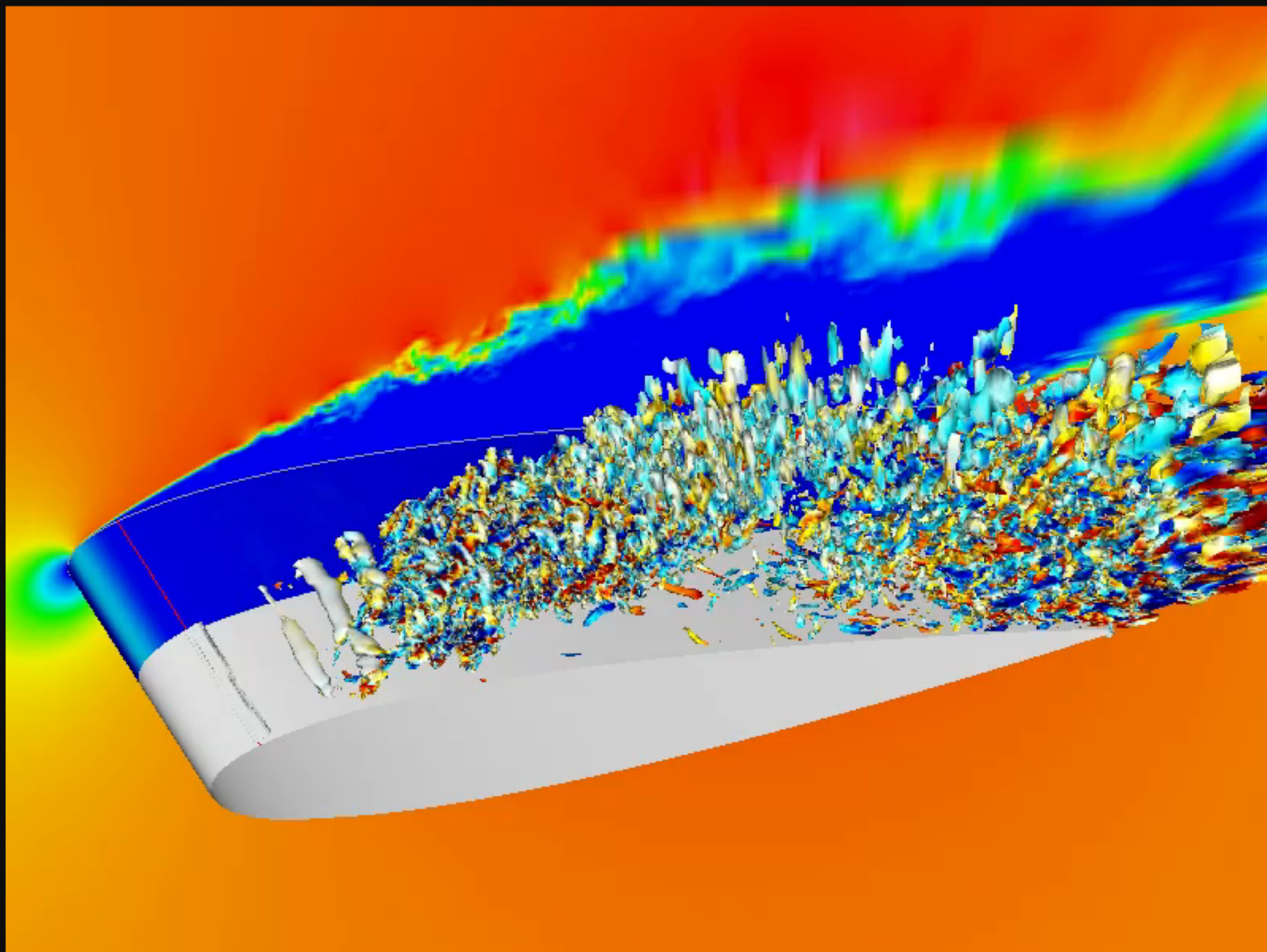


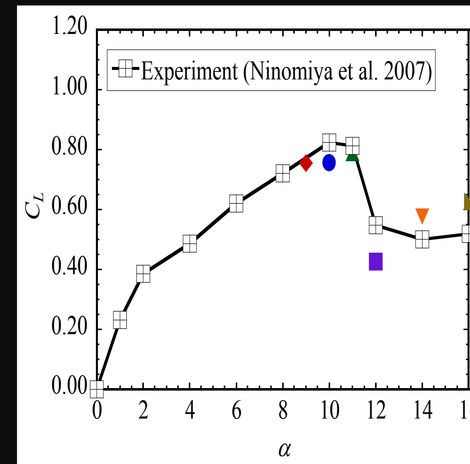
NACA0006

Questions remained

- Why burst mode works better than continuous mode?
- Why is "F^+=1" effective at certain conditions?
- Why did both our experiment and computation show "F^+=6" effective as well?
- What kind of flows are induced by PA and how do they influence to the flow control authority?

Flow Separation Control by DBD Plasma Actuator



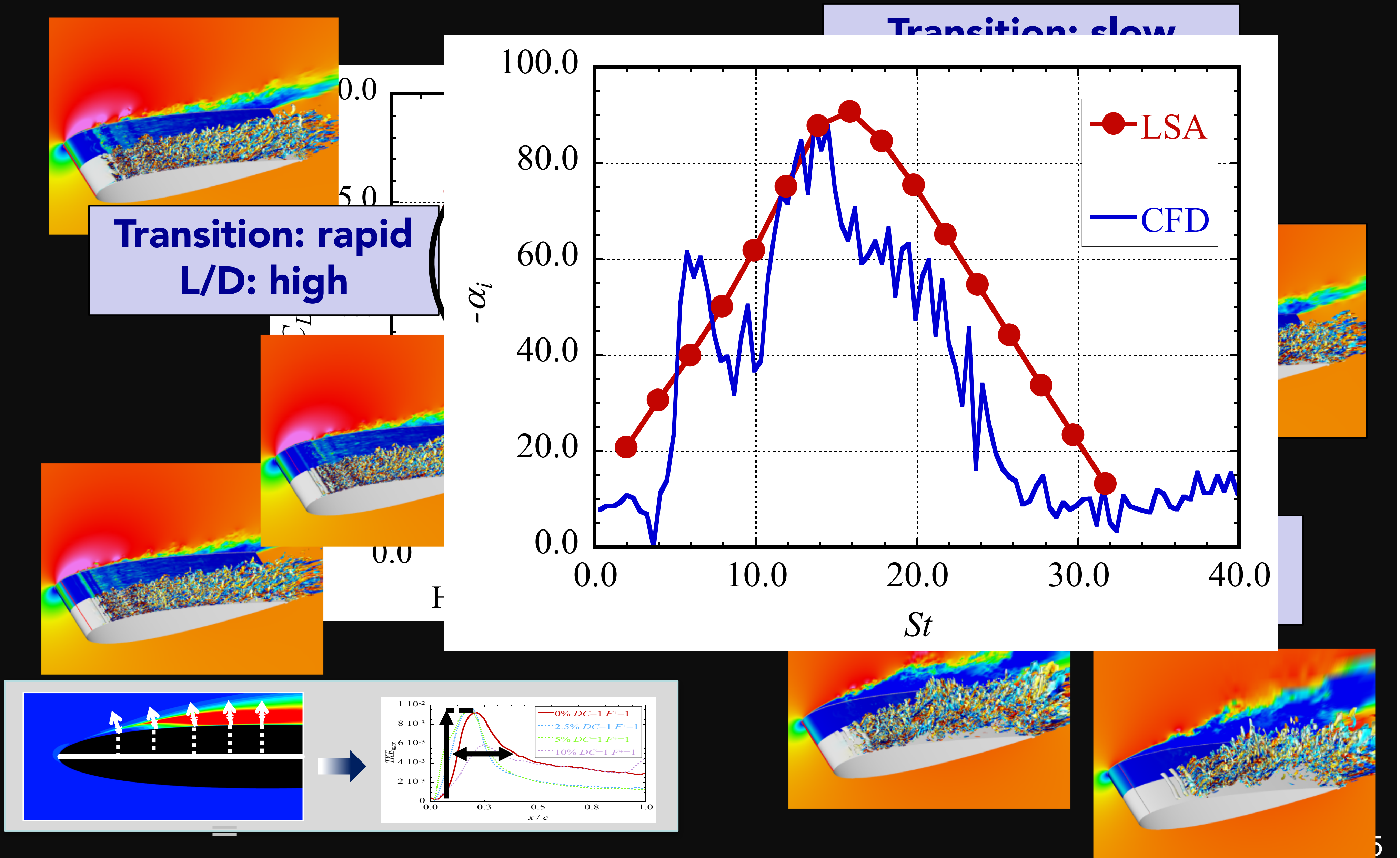


NACA0015: α = 12 deg. Re = 63,000

DBD-PA at 5 % chord, with F^{+}=6.0, 10% burst ratio

Ref. Sato, Fujii, et al. Phys. Fluids. Vol. 27, 117101, 2015

Single Mechanism?

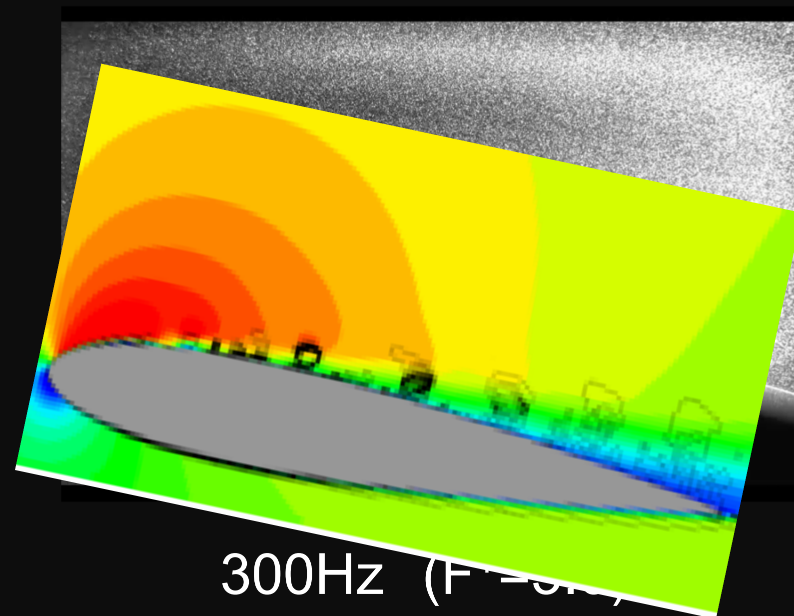


a = 12 deg. , Re = 63,000

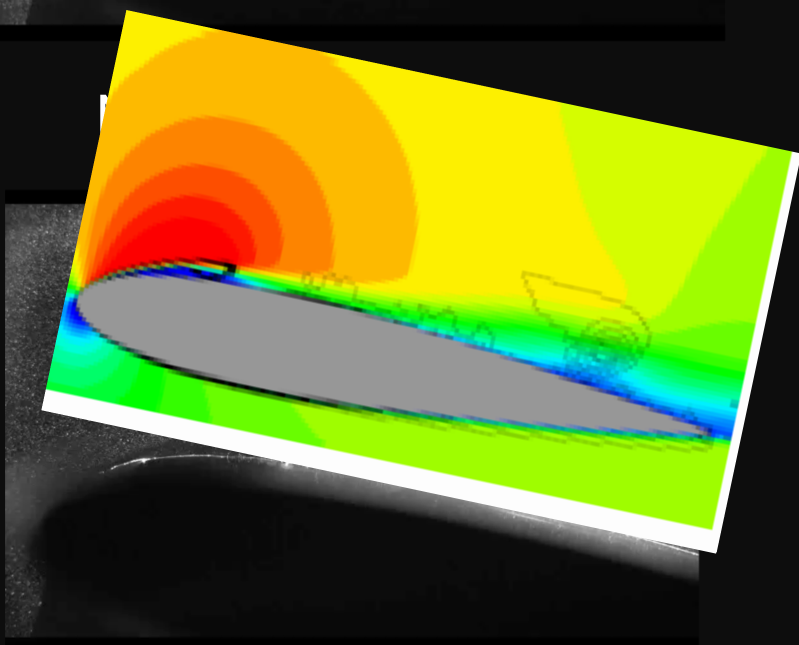
Back to the flows at $Re=6.3\times10^4$

Stall angle ＋1°

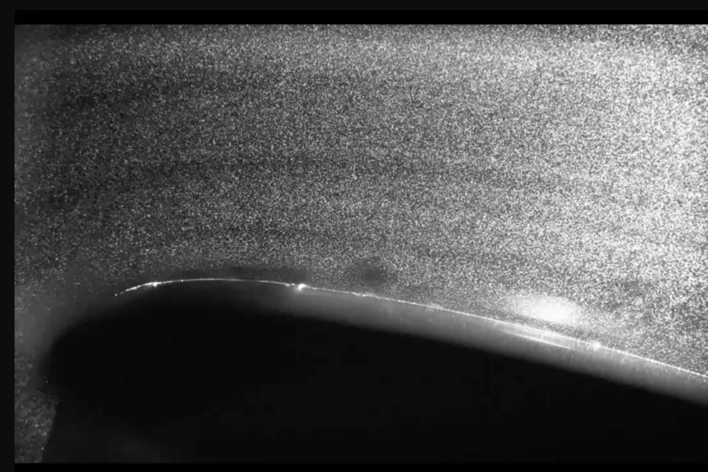
(NACA0015， X/C=5%)



300Hz (F



100Hz (F+=1.0)



1000Hz (F^+=10.0)

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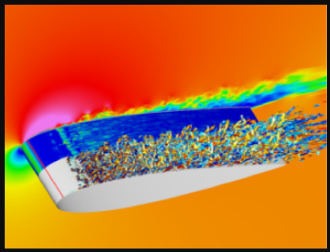
前縁剥離法，遷移，乱流境界層，2次元渦構造

How to suppress flow separations with DBD-PA

Flow Separation Control at Relatively Low Re Numbers



Three mechanisms

- Promote transition with induced disturbances
- Create strong coherent vortex structures
- Add streamwise momentum

（1）high frequency bursting (K-H instability) effective

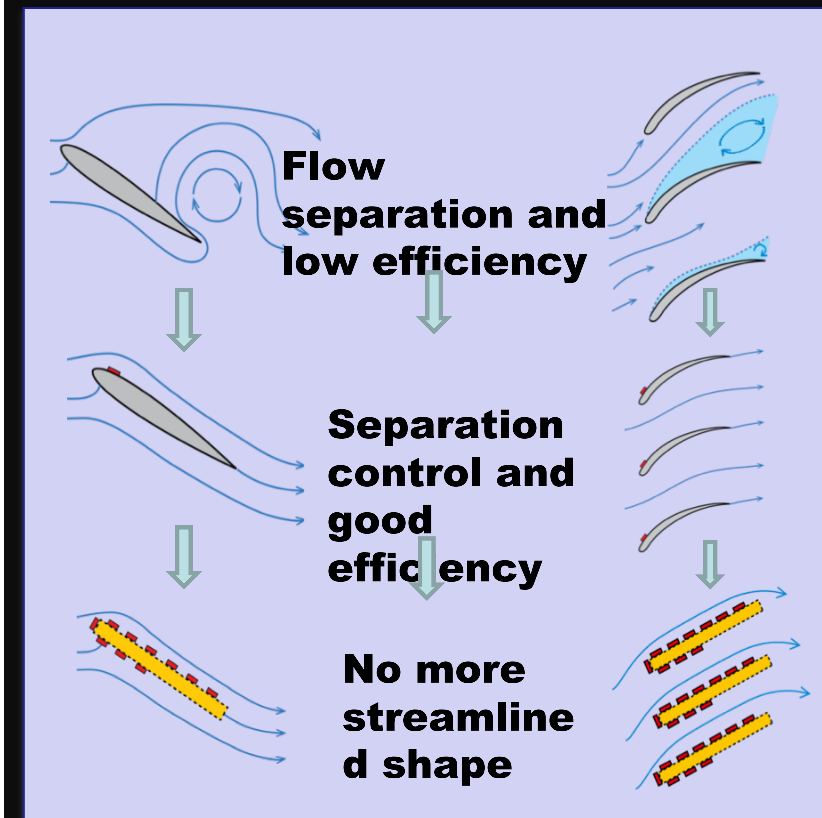
（2）low frequency bursting effective

（3）continuous actuation with strong electric power effective

Control Strategy

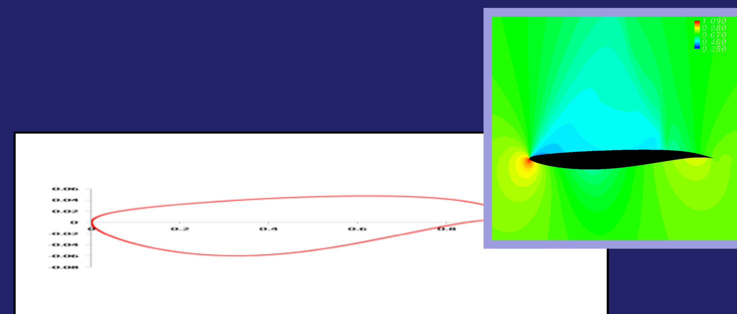
- Use (1) when shear layer located near the wing surface
- Use (2) when shear layer located away from the wing surface?
- (3) is always important and effective in general

Toward Aerodynamic Design Innovation

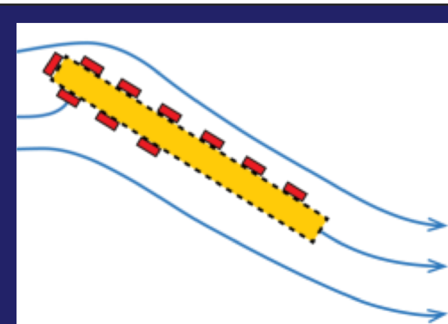


Innovation for wing design

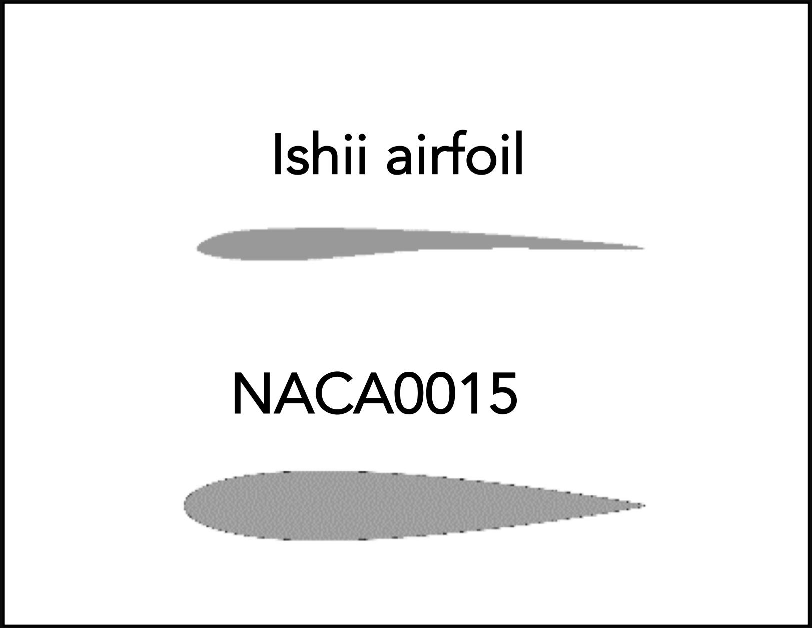
Geometry-based design

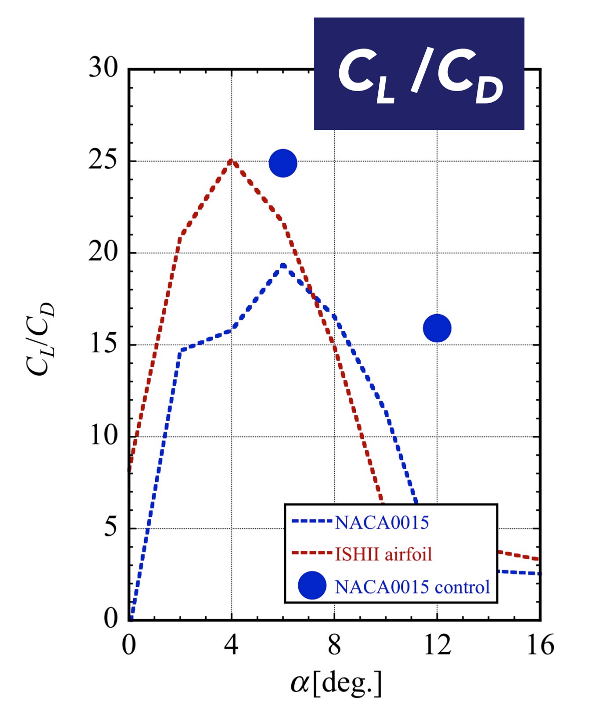


Design with micro devices

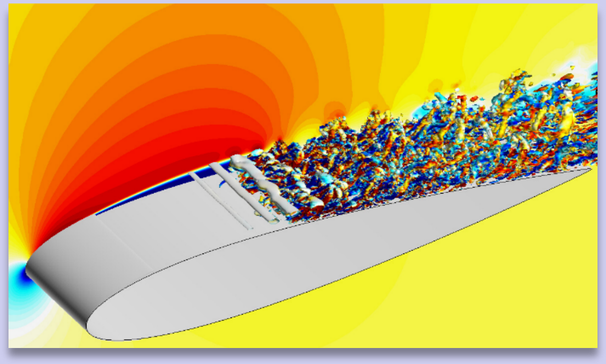


Possible use of DBD-PA at cruise conditions

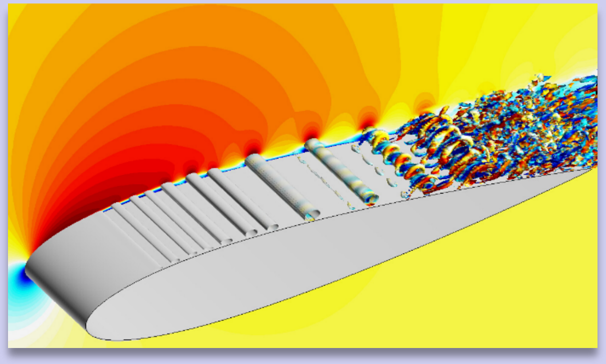




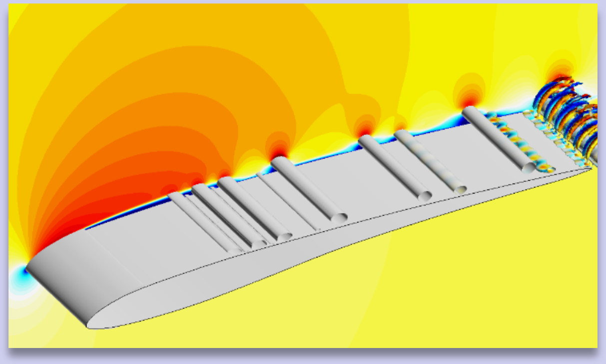
NACA0015 OFF



NACA0015 *F*⁺=6

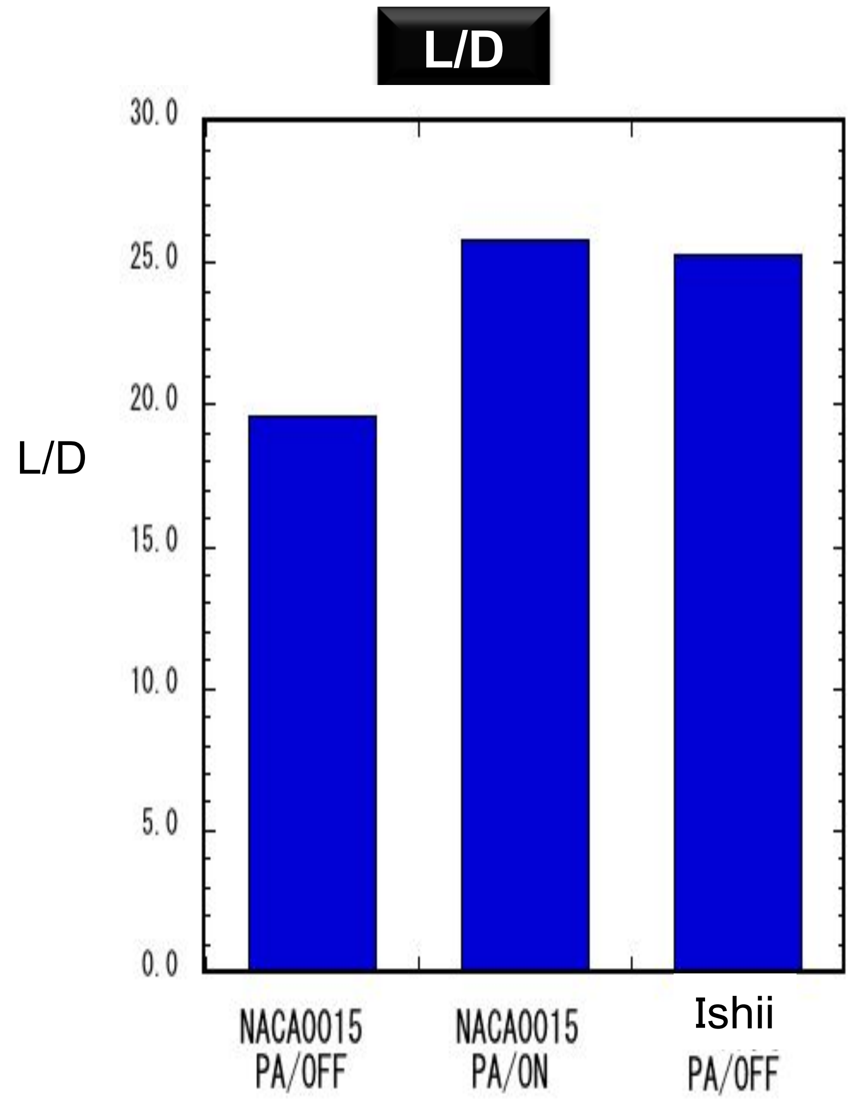


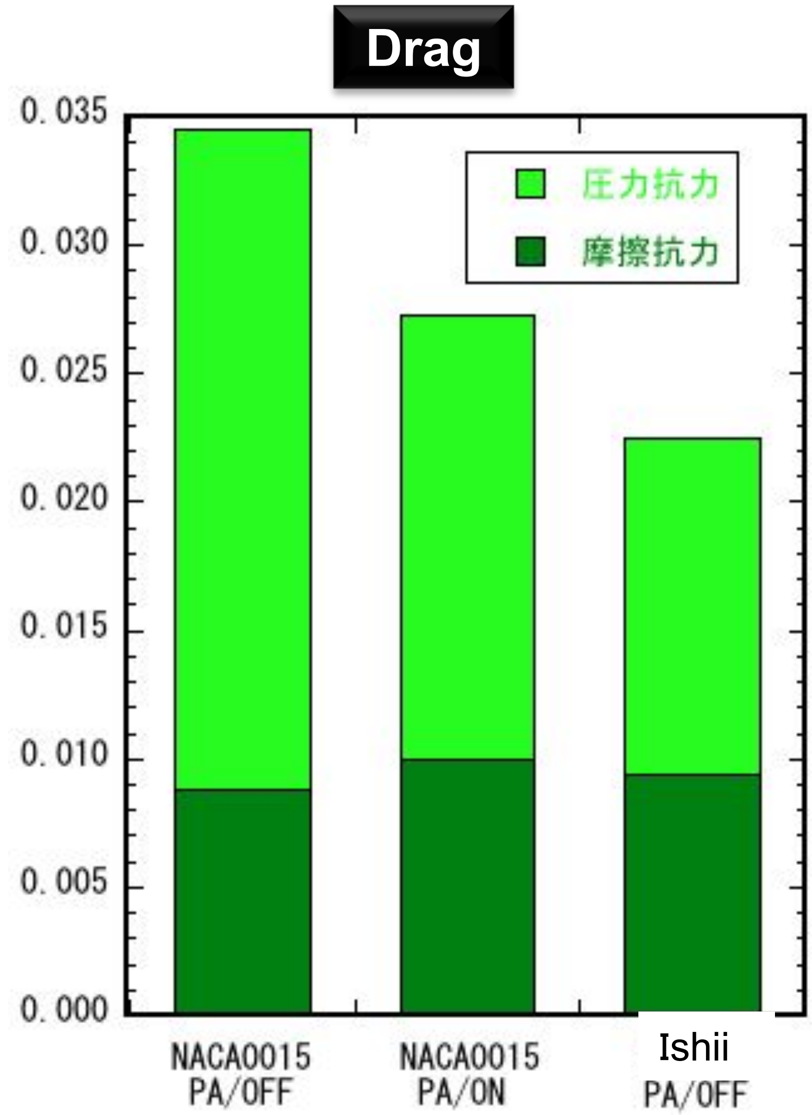
Ishii OFF



Asano, K. et al. AIAA 2016-3624

Effect of DBD-PA at cruise condition

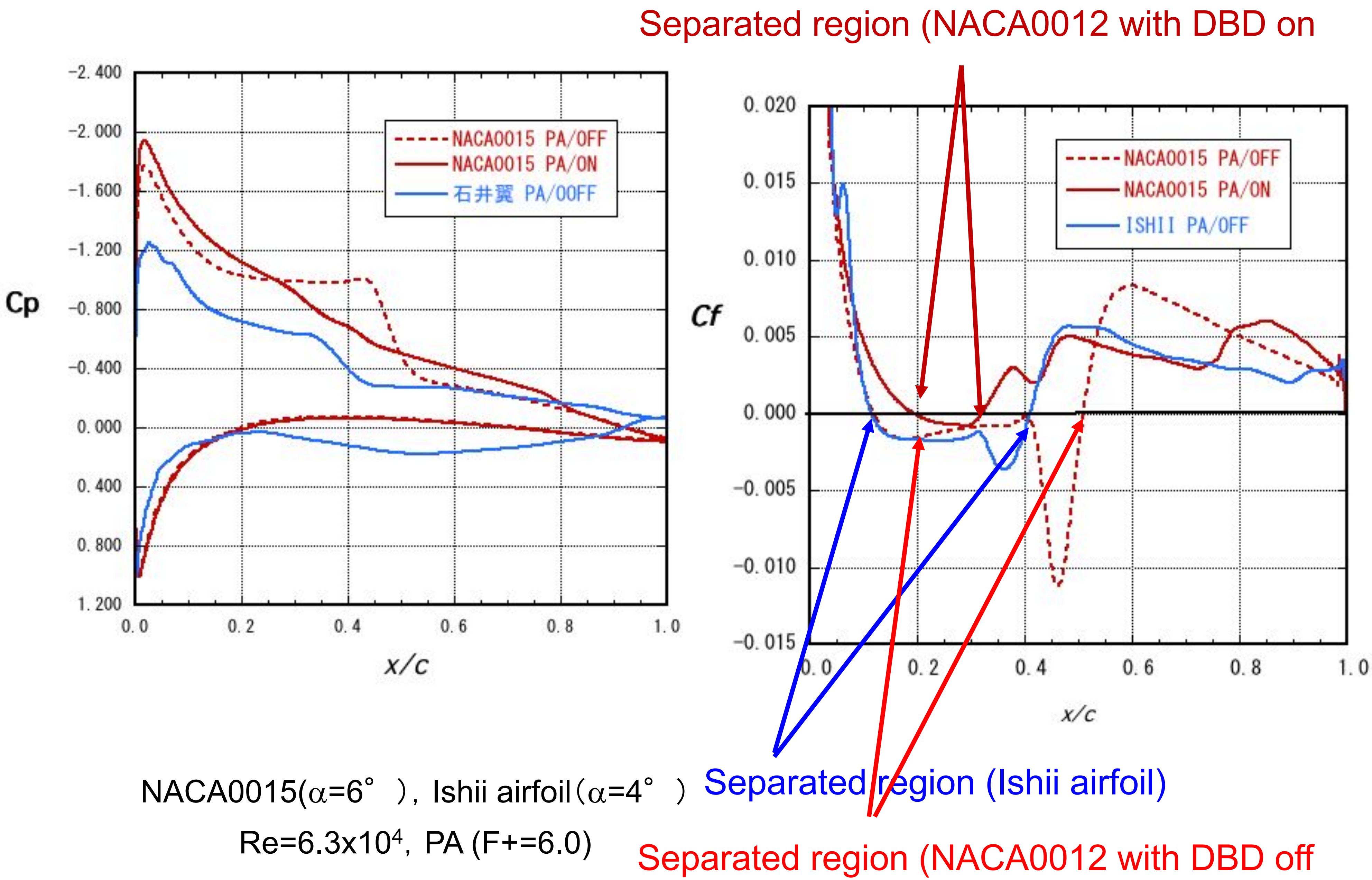




NACA0015(a=6°), Ishii airfoil (a=4°)

Re=6.3×10^4, PA $F^+ = 6.0$

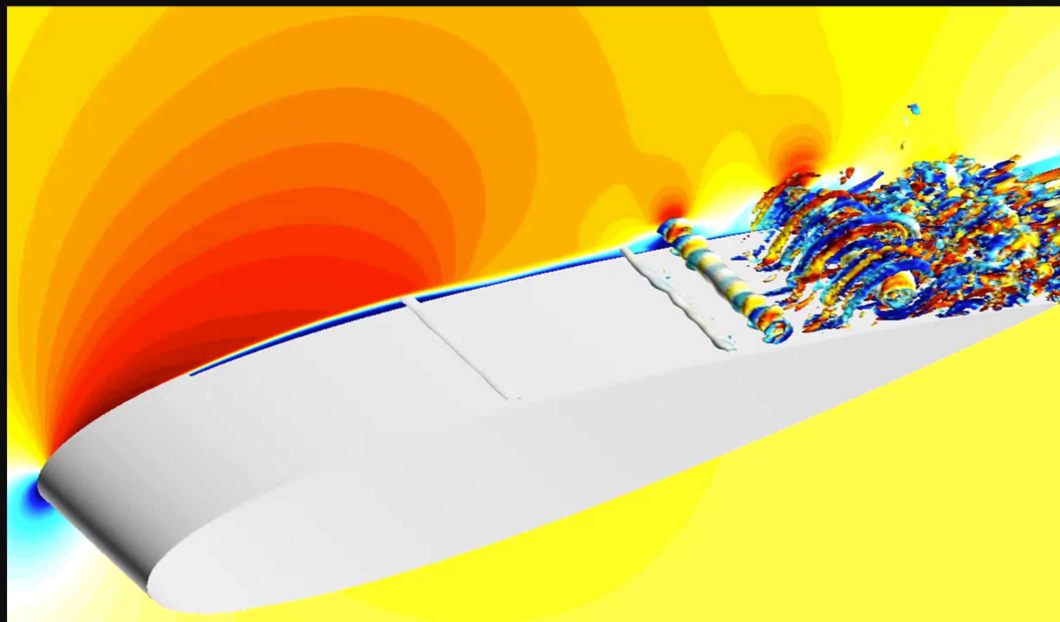
Cf's and Cp's over the airfoil surface



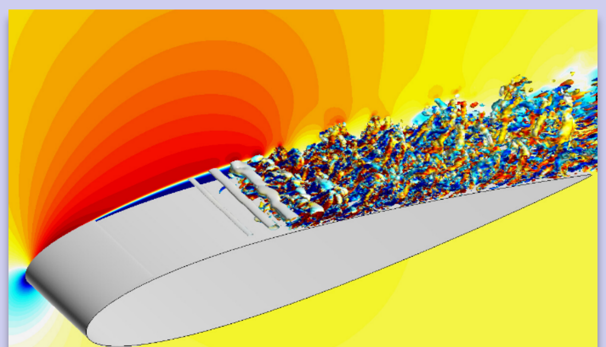
NACA0015(α=6°), Ishii airfoil(α=4°)

Re=6.3x10^4, PA (F+=6.0)

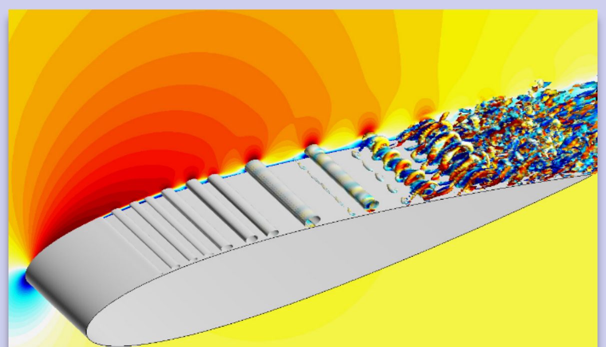
Flow structures



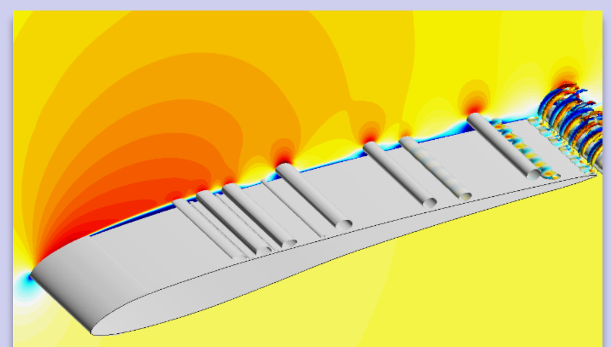
NACA0015 W/O PA



NACA0015 with PA (F^+=6)



Ishii W/O PA

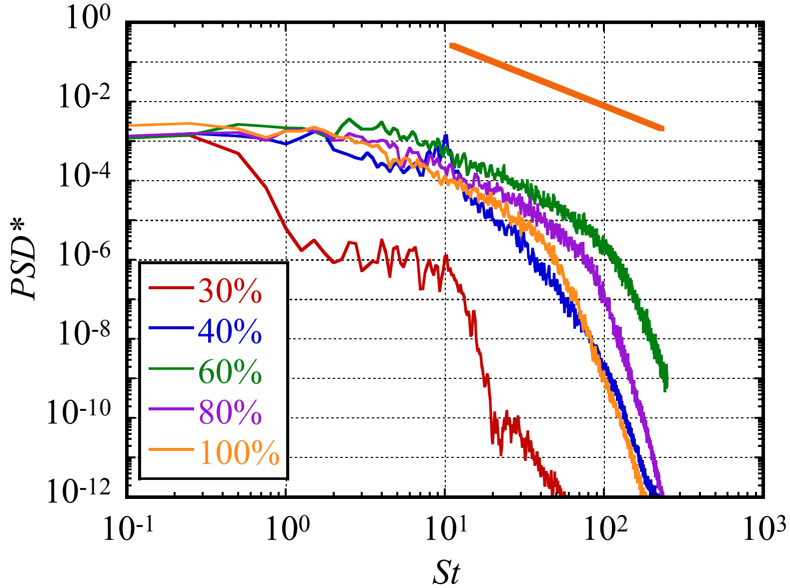


Asano, K. et al. AIAA 2016-3624

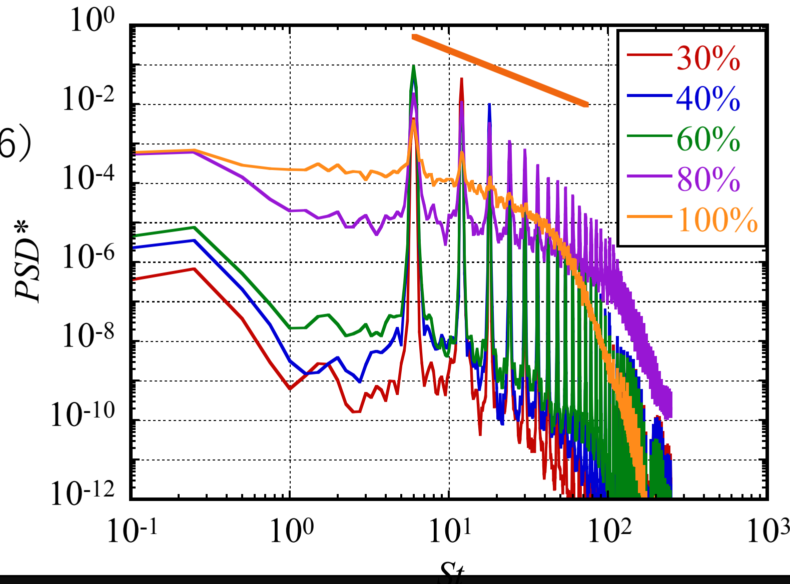
PSD Analysis of chordwise velocity fluctuations

NACA0015

OFF

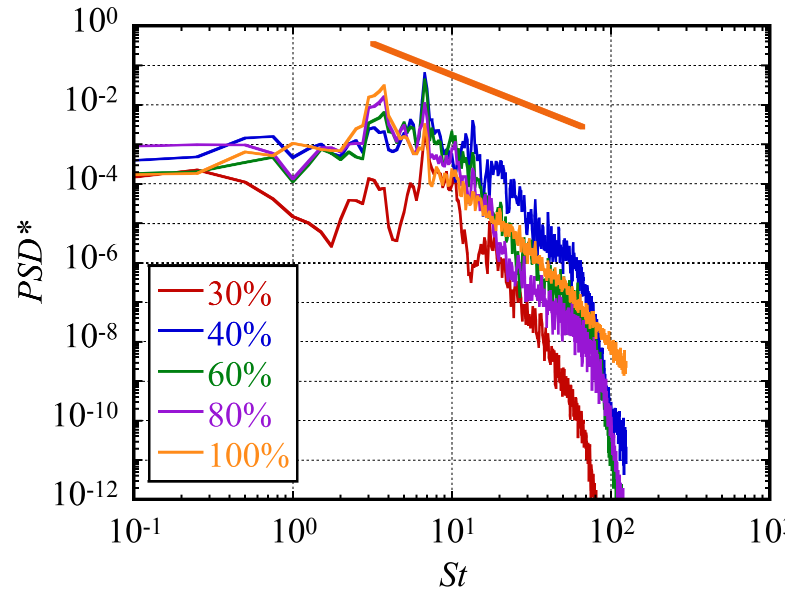


ON (F⁺=6)



Ishii airfoil

OFF



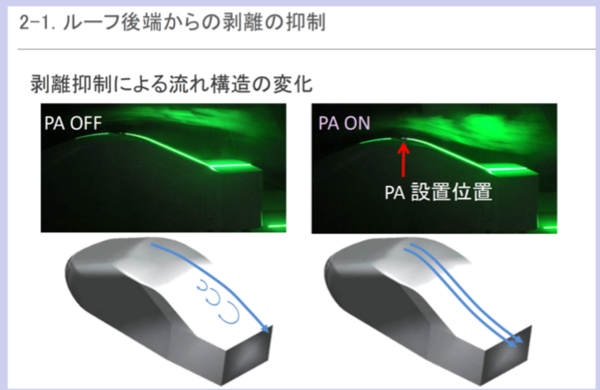
Practical Applications of DBD-PA

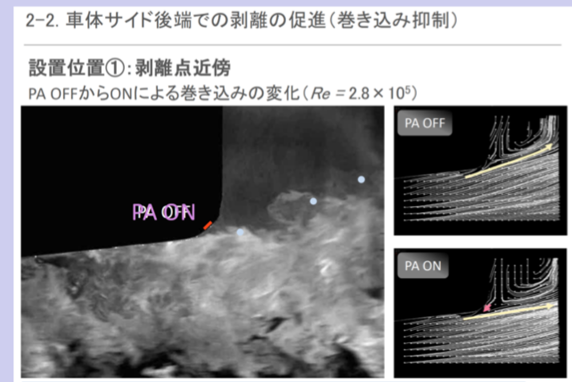
Taken from each website

1.75MW Wind Tu

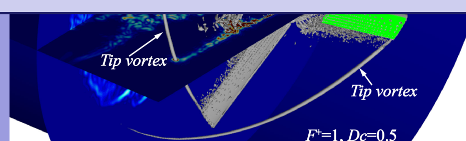
M. Tanaka, et al. (TOSHIBA) , F
Aerodynamic Controlled Wind

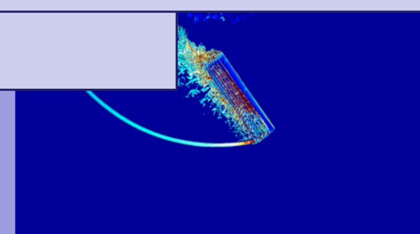
Application to automobiles





Keigo Shimizu et al.
4th Plasma actuator Symposium (Domestic)
Sendai, March 2017





Summary

- Progress of HPC and spectral-like high-order schemes are making large-scale LES simulations feasible for industrial applications.

- Conceptual design is the most beneficial use of CFD although cost and time reduction by CFD are also important and useful.

- CFD even in conceptual design may sometimes require large scale computations because of nonlinearity and stiffness of fluid dynamics.

Reference

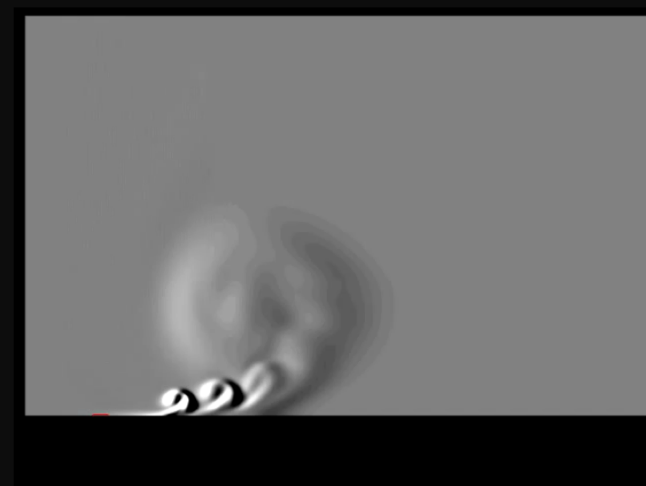
Fujii, K. "High-performance computing based exploration of flow control with micro devices," Philosophical Transactions A, The Royal Society, Vol. 372, Article ID 20130326、2014

Fujii, K., "Progress and Future Prospects of CFD in Aerospace –Wind Tunnel and Beyond," Progress in Aerospace Sciences, Vol. 41, No. 6, 2005.

Plasma model validation

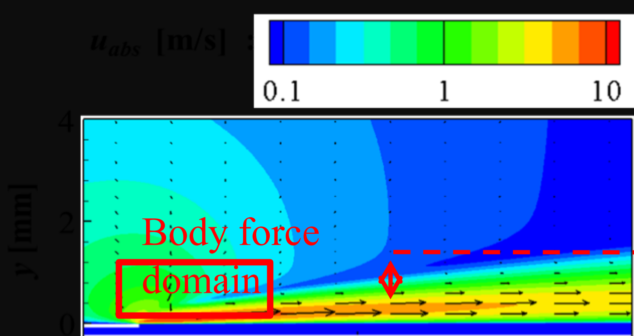
- **Induced flows**

Experiment (F⁺=1, BR=0.1, Vpp=10Kv)

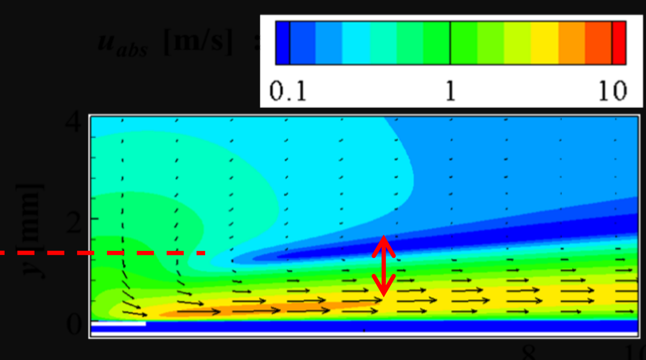


Simulation（F⁺=1, BR=0.1, Dc=0.0625）

- **Suzen plasma mode l (work by Koizumu and Nisida)**



Detailed plasma model



Suzen model

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Validation of the Approach

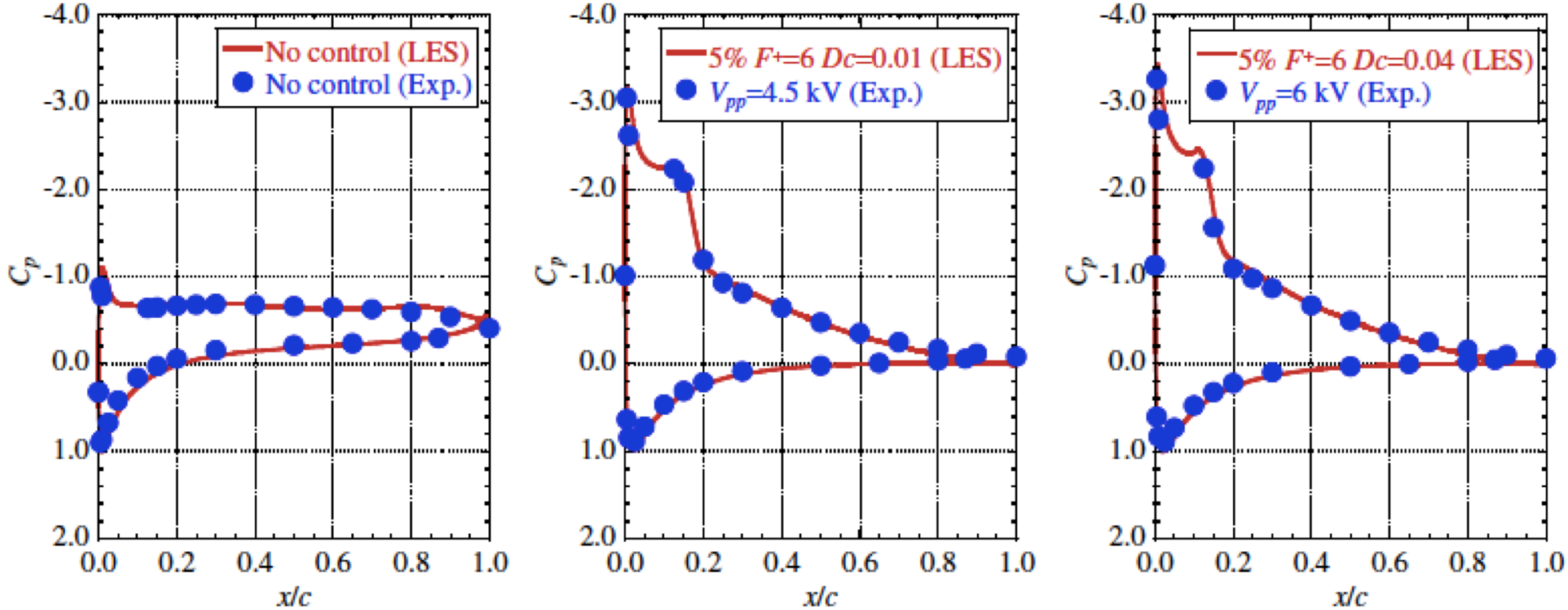

Fig. 6 Mean pressure coefficients along the airfoil for computational and experimental (Exp.) results.